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ICE FREEZE-UP AND BREAKUP IN THE LOWER THAMES RIVER: 1981-82 OBSERVATIONS

by

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ABSTRACT

The third year's ice observations on the lower Thames River are described and interpreted. Freeze up commenced in December 1981 and was followed by two moderate runoff events that caused partial breakups in late December and early January. Subsequently, cold weather resumed and the main breakup occurred in March 1982. Several ice jams formed during this event throughout the study reach, resulting in moderate flooding near Prairie Siding.

The breakup patterns observed to date suggest a sub-division of the study reach into two subreaches, Bothwell to Chatham and Chatham to mouth. In the first subreach, breakup is governed by water stage and channel width relative to the size of ice sheets that form by transverse cracking of the winter cover. This pattern is consistent with a previously developed conceptual model and the 1982 observations on crack spacing, breakup initiation and jam release are in agreement with the consequences of the model. In the second subreach, i.e., Chatham to mouth, where significant lake effects on stage are present, a different type of breakup occurs, consisting of thermal deterioration and mechanical disintegration of the winter cover, associated with an intermittently advancing jam.

Measured ice jam stages adhere to a previously developed dimensionless relationship that is based on the theory of equilibrium jams.

RESUME

Les observations portant sur les glaces du cours inférieur de la rivière Thames durant la troisième année sont décrites et expliquées. L'embâcle a commencé en décembre 1983: deux écoulements modérés ont ensuite causé des dégels partiels à la fin de décembre et au début de janvier. Les températures froides sont ensuite revenues et le dégel principal est survenu en mars 1982. Plusieurs embâcles se sont formés durant cette période tout le long du tronçon de la rivière à l'étude, causant des inondations modérées près de Prairie Siding.

Les mécanismes du dégel observés jusqu'à maintenant suggèrent que la portion de la rivière à l'étude se divise en deux sous-branches: de Bothwell à Chatham et de Chatham à l'embouchure. Dans le premier segment, la débâcle dépend du niveau de l'eau et de la largeur du canal par rapport à la taille des pans de glace qui sont formés par la fissuration transversale de la couverture de glace hivernale. Ce phénomène est compatible avec un modèle conceptuel mis au point plus tôt, et les observations de 1982 sur l'écart des fissures, le déclenchement des débâcles et le déblocage des embâcles sont conformes aux hypothèses qui sous-tendent le modèle. Dans le deuxième segment, c'est-à-dire de Chatham à l'embouchure, l'influence des différents niveaux se fait fortement sentir. Il s'y produit un genre différent de débâcle, c'est-à-dire qu'on constate une détérioration thermique et une désintégration mécanique de la couverture de glace hivernale, associées à une progression irrégulière de l'embâcle.

Les mesures des niveaux d'embâcles appuient la relation sans dimensions élaborée antérieurement qui reposent sur la théorie des embâcles flottants en équilibre.

MANAGEMENT PERSPECTIVE

This is the third report from a continuing program of annual freeze up and breakup observations aimed at developing solutions related to ice-jam flooding.

The data presented in this report support a conceptual model developed at NWRI to predict the onset and severity of breakup for the upper portion of the study reach. The breakup pattern is more complex in the lower portion of the study reach where water levels are strongly influenced by Lake St. Clair.

Several major jams were recorded and the documentation supports use of an existing theory.

More data are needed for a complete understanding of ice jam and flooding processes.

T.M. Dick
Chief
Hydraulics Divisions

PERSPECTIVE-GESTION

Le présent rapport est le troisième dans le cadre du programme d'observation de l'englacement et de la débâcle qui surviennent à chaque année. On cherche à élaborer des solutions aux problèmes associés aux crues causées par les embâcles.

Les données recueillies et présentées ici soutiennent un modèle conceptuel mis au point à l'INRE dans le but de prévoir le moment de la débâcle et sa gravité dans la partie supérieure du tronçon à l'étude. Les caractéristiques de la débâcle sont plus complexes dans le tronçon inférieur du territoire couvert par l'étude, là où les niveaux d'eau sont fortement soumis à l'action du lac St-Clair.

Plusieurs embâcles importants ont été étudiés et les renseignements obtenus confirment la valeur de la théorie actuelle.

Il est nécessaire d'obtenir davantage de données afin de mieux comprendre le mécanisme des embâcles et des crues.

Le chef,
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Division de l'hydraulique

1.0 INTRODUCTION

A major component of the Hydraulics Division's ice jam research program is the annual documentation of ice regime and jamming in two Southern Ontario river reaches, i.e., the lower Thames and the upper Grand Rivers. This is a long-term effort, initiated in late 1979, aimed at both quantification of ice-related phenomena in the observation reaches and improvement of qualitative understanding as a guide to laboratory and theoretical research.

This report pertains to the Thames River and describes the results of the third year's observations. Earlier reports (Beltaos 1981; 1983a) contain more detailed information on the rationale and objectives of the field observation program. The Thames River study reach extends from about Bothwell to the river mouth in Lake St. Clair (Fig. 1). An approximate water surface profile of the river, from the mouth to Middlemiss, is shown in Fig. 2. Water surface elevations have been obtained from a series of 1:25,000 topographic maps at the intersections of elevation contours with the stream boundaries. Straight lines have been drawn between points representing successive contour intersections. Relevant information, such as river crossings, towns, tributaries and the like are also shown in Fig. 2. Additional hydrologic and hydraulic data are included in an earlier report (Beltaos, 1981).

2.0 FREEZE UP AND WINTER

Figure 3 shows the daily average stage hydrograph at the Thamesville gauge along with temperature and rainfall data at Ridgetown, located some 11 km from Thamesville. Persistent cold weather began on December 8, 1981, and Water Survey of Canada estimated that ice effects on stage commenced on December 18. The corresponding degree-days of frost and river discharge are estimated as 35.3°C-days and 27.8 m^3/s. In situ observations indicated that, on December 14, there was no

stationary ice on the river except for a short reach starting at the river mouth and extending a few hundred metres upstream. However, by December 20, there was complete ice cover with occasional open leads at least as far upstream as the Dutton crossing. The Thamesville hydrograph (Fig. 3) shows a peak of 11.48 m on December 19 which occurred under falling discharge conditions. This peak is thus assumed to signify the formation of complete ice cover at Thamesville.

Rainfall on December 22 caused the stage to rise, leading to a peak on December 23 (Fig. 3). Observations on December 26 revealed that this runoff event did not generally dislodge the ice cover except at isolated areas. For example at the Thamesville crossing there was a 200 m long open-water section just upstream of the bridge. A period of moderate cold followed this event, until January 3, 1982, when additional rain fell, followed by two days of positive air temperatures. The resulting runoff event initiated breakup of the ice cover at several locations as well as formation of a few minor jams.

Observations during January 5 and 6 revealed the following:

- Middlemiss crossing: about 400 m long open-water section, centered at the bridge.
- Dutton crossing: ice cover with 1-5 m wide open-water strips at the sides.
- Highway 75 crossing: open water upstream near right bank for about 50 m, followed by ice cover to limit of visibility (≈600 m). Open water downstream near right bank for about 50 m, followed by 300 m long section of ice cover. Open water further downstream to limit of visibility (≈700 m).
- Wardsville crossing: ice cover with open patch near midstream. Minor jam about 100 m upstream of the bridge. Areas of open water downstream of the bridge.
- Bothwell East and Bothwell West crossings: open water.
- Fairfield Museum: open water with 1-5 m wide strips of ice along the sides.

- Tecumseh Monument: ice cover with 1-3 m wide open water strips at the sides.
- Thamesville crossing (Highway 21): open water for about 700 m upstream and 1100 m downstream of the bridge. Minor ice jams near this location.
- Railway bridge near Thamesville: open water to at least 300 m upstream and about 300 m downstream of the bridge.
- Kent Bridge: ice cover but with mid-channel open lead starting 10 m upstream and ending 150 m downstream of the bridge, almost full river width at upstream end but tapering off to a point at the downstream end.
- Golf Course to Chatham: ice cover.

In summary, breakup was initiated at various locations upstream of Kent Bridge but did not progress to any appreciable degree. Downstream of Kent Bridge, the ice cover remained intact.

After January 6, a period of sustained frost started and the ice cover remained in place until the final breakup in March. Ice thickness measurements were performed during this period and the results are summarized in Table 1. Ice thickness is seen to increase with time and there is also a general trend to increase in the downstream direction.

Photos of freeze up and winter conditions are presented in Appendix A.

3.0 MARCH BREAKUP

Figure 3 shows that considerable rainfall occurred on March 3, but resulted in little runoff, as indicated by the stage hydrograph at Thamesville. The daily average air temperature rose above 0°C on March 11 and remained positive for the next 14 days. Significant rainfall occurred on March 11, 12 and 16, leading to breakup and complete clearance of the ice from the study reach by March 22. Field

observations commenced on March 12 and a description of breakup events is given next.

March 12. At the Highway 21 crossing near Thamesville, the ice cover was intact with open water strips at the sides. For photographs of various breakup features see Appendix B.

March 13. The river remained mostly ice-covered between the mouth and Middlemiss. No side strips of open water were observed near the mouth; very narrow side strips were present near Chatham, increasing in width in the upstream direction and becoming of significant size at Thamesville. Open water sections and localized ice breakage were noticed occasionally, mostly near tributary mouths. At the Thamesville gauge site (Highway 21), breakup was initiated between 1908 h and 2045 h. For water level and ice conditions at this site, see Fig. 4 and Appendix C. Ice breaking operations commenced at the river mouth in late afternoon (see photos in Appendix B).

March 14. Mostly minor jams developed between Bothwell and Thamesville, leaving substantial river sections open. Significant jams were observed near Bothwell West crossing and near Fairfield Museum. The location of the latter jam is shown in Fig. 5. The river remained ice covered below Kent Bridge with narrow open-water strips at the sides. Ice breaking at the river mouth continued.

March 15. The water level at Thamesville rose slightly. Ice continued to move downstream and formed a surface jam in the vicinity of the Highway 21 bridge. The jam at Fairfield Museum remained intact. The water level at Kent Bridge remained constant and ice conditions did not change appreciably (see Appendix D). Between Kent Bridge and Sherman Brown Bridge, ice conditions changed little but transverse cracks began to form. In Chatham, open-water strips at the sides had widened and by 0845 h, there was evidence of imminent breakup initiation (transverse

cracks, local crushing, short open-water sections). A short jam had formed upstream of the Third St. Bridge by 1825 h (see photos in Appendix B). The ice in this jam appeared to be of good quality; ice floes accessible from the river banks had roughened bottom and ranged in thickness from 15 to 38 cm, averaging about 28 cm.

March 16. Rain started at 0840 and continued until about 1500 h (see also Fig. 3). The jam at Fairfield Museum remained intact until 1505 h when a large portion of it released, only to jam again a few kilometres downstream. At Thamesville, the water level rose slightly. The surface jam that had formed on March 15 released at about 1830 h but was arrested after travelling a short distance downstream. At Kent Bridge, the ice cover had shifted slightly during the night but was largely intact at 0750 h. The water level rose slightly during the day and breakup was initiated between 1625 h and 1940 h. Ice upstream of the bridge was held stationary, however, by a large sheet wedged between one of the piers and the right bank (see photos in Appendix B). The ice cover between Kent Bridge and Sherman Brown Bridge remained in place. No major changes occurred in Chatham until 1740 h but ice movements had taken place by 2100 h.

March 17. Water levels continued to rise slowly at Thamesville and Kent Bridge. Aerial reconnaissance during 1230-1340 h, revealed the following conditions.

- Ice jams upstream of both Bothwell crossings; below Fairfield Museum, near the railway bridge at Thamesville; and upstream of Kent Bridge (see Fig. 6 and photos in App. B).
- Between Kent Bridge and Sherman Brown Bridge there were numerous transverse cracks and a few areas where the ice had moved, causing local breakage and formation of open-water sections (Fig. 7). The ice in Chatham had broken up and was gathered in a jam downstream of the town (Fig. 8).

The two jams near Bothwell must have released shortly before 1630 because an ice run was observed at Fairfield Museum at this time while the Bothwell crossings were found open at 1640 h.

March 18. Water levels continued to rise slowly at Thamesville and Kent Bridge but remained constant at Sherman Brown Bridge (see also Appendix E). The jams near the railway bridge at Thamesville had released during the night. The jam at Kent Bridge remained in place except for a brief movement during 1248-1303. By 1630, a jam had developed near Louisville, as sketched in Fig. 9. In Chatham, the river was open except for a minor jam near the LTVCA office. By 1205, the jam downstream of Chatham was about 750 m long and the head was near the historical monument (Fig. 10).

March 19. Overnight, the water level dropped slightly at Kent Bridge. The jam released at 1025 and this was accompanied by a sharp rise in stage (see Appendix D). Most of the broken ice had passed under the bridge by 1052 but the ice run was arrested at a sharp bend 2 km downstream by a large ice sheet (Fig. 11; photos in Appendix B).

The jam near Louisville released overnight and the river was found open between Kent Bridge and Sherman Brown Bridge at 0700-0710 h. At 0755, a 2.7 km long jam was observed near the north end of Chatham but released prior to 0820. According to LTVCA (lower Thames Valley Conservation Authority), the small jam near their office released at 0830.

The jam near Kent Bridge released at 1343 and moved unimpeded downstream where it eventually joined the jam below Chatham. By 1500 h, the only jam in the river was near the Prairie Siding crossing with open water upstream and intact ice cover downstream. The toe of this jam was about 800 m downstream of the bridge and the head about 800 m upstream. At 1543, the jam moved and a new toe formed farther downstream of the bridge. From this time, a steady stream of ice floes was adding to the jam. The jam lengthened and by 1810, the head was approximately 400 m

upstream of the bridge (Fig. 12). Flooding occurred at several locations, mostly on the right bank, between Chatham and Prairie Siding. By 1630, the water had risen over the right bank road about 0.75 km upstream of the bridge and escaped into the corn fields. Most of the houses on both sides of the river were just above the ice and water (see photos in Appendix B). The ice cover below the toe of the jam remained competent though the snow cover had melted away. There were no transverse cracks and only very narrow strips of open water at the sides. By 1620 h ice breaking operations had succeeded in clearing the section between the river mouth and the OMNR docks (photo, Appendix B).

March 20. No changes occurred overnight. At 0700, the left half of the ice cover at the toe broke up and moved 250 m downstream. The toe of the jam, however, remained in place. At 1135, more of the ice cover on the left half of the river broke and moved another 250 m. The jam released at 1400 and was arrested again 2 km downstream, near St. Peter's church. Observations were discontinued at this time.

March 21 and 22. LTVCA has indicated that the ice cover from the OMNR docks to Bradley broke up on March 21. By 1800 h on March 21, the jam had released and all the ice floes were arrested near the mouth of the river. By 0300 on March 22, the floes had moved out into Lake St. Clair.

3.1 Summary of Breakup Observations

In general, the (main) 1982 breakup progressed in the downstream direction. Within the reach Bothwell to mouth, breakup started first near Fairfield Museum and Thamesville in the evening of March 13. At Kent Bridge and Sherman Brown Bridge crossings, breakup was initiated between March 16 and 18. It is noteworthy that breakup initiation through and below Chatham occurred independently of upstream ice conditions much as happened in 1980 and 1981.

Major jams occurred near Fairfield Museum, Kent Bridge, Louisville, and Prairie Siding. From Chatham to the mouth, the breakup process consisted of intermittent movements of a jam that kept breaking through the undisturbed ice cover and advancing downstream, much as was observed in 1981. This jam caused moderate flooding that started on March 19.

4.0 DATA ANALYSIS AND INTERPRETATION

4.1 Initiation of Breakup

An important consideration for short-term forecasting is how to predict when breakup is to start. By defining breakup initiation as the time when a sustained movement of the winter ice cover begins, it has been possible to show that forecasting can be made in terms of the prevailing water stage, H_B (e.g., gauge height or water surface elevation when breakup is initiated). Previous work (Shulyakovsky 1963; Beltaos 1984b) suggested that H_B depends mainly on H_F (= stage at formation of a stable ice cover during freeze up); h_i (= ice cover thickness); and competence of the ice cover. The latter parameter is difficult to quantify at present and is customarily substituted by an index of thermal imputs to the ice cover prior to breakup initiation. These ideas lead to site-specific correlations between H_B, H_F, h_i, and a thermal index, that may be used for short-term forecasting.

Beltaos (1983b, 1984d) proposed a conceptual model of the breakup process which has given some encouraging results for several rivers. Briefly this model is based on the hypothesis that under certain conditions, breakup is initiated when the water surface width is sufficient to permit ice sheets, formed by transverse cracking of the cover, to clear bends or other obstacles. During the 1982 breakup it was possible to directly confirm this hypothesis for the Thames River, by means of aerial observations performed on March 17. Figure 7 shows the locations of transverse cracks observed prior to breakup initiation in a reach between Chatham and Kent Bridge. Moreover, it has been shown elsewhere (Beltaos, 1984d) that the spacing of these cracks is

consistent with what would have been expected from channel width values corresponding to observed breakup initiation stages.

Because of the two runoff events in early winter, this year's breakup is not as straightforward as those of previous years and requires considerable interpretation in order to arrive at suitable values of H_B and H_F. Below is an outline of the interpretation adopted herein.

First Runoff Event. Following freeze up and complete ice cover formation at Thamesville on December 19 (H_F = 11.48 m), rain on December 22 caused the stage to rise, leading to a peak of 12.36 m at 2000 h on December 24. Observations on December 26 indicated that, while there was some local breakage, there had not been downstream movement of the ice cover. Thus, H_B for this event is set to exceed 12.36 m though it is not known by how much. The ice cover thickness applicable to this event at Thamesville is estimated as 12 cm, based on an analysis of earlier measurements and accumulated degree-days of frost.

At Kent Bridge, complete ice cover formation occurred on or shortly before December 19. From stage measurements on December 20 and a previously established correlation between Thamesville and Kent Bridge stages under ice conditions, the value of H_F is estimated as 175.61 m (geodetic elevation). On December 26, no change in ice conditions was observed while the peak stage during this runoff event at Kent Bridge is estimated to have been 176.40 m, occurring on December 25. The value of h_i is estimated as 15 cm.

At Sherman Brown Bridge, measurements on December 20 and examination of the Chatham gauge record indicated a value of 175.16 m for H_F, occurring on December 18. On December 26, there was no change in ice conditions while the water level was at 176.26 m.

Second Runoff Event. While the water level rose above H_F during the first event, observations and weather data indicated that there was

little opportunity for new ice to form at these higher stages. Hence H_F remains unchanged for the three sites under consideration. Rain on January 3 and 4 caused renewed runoff while observations on January 5 indicated that breakup had been initiated at the Thamesville gauge site. However, it is not known when initiation occurred. It can be assumed that $H_B \leq 13.62$ m at about noon of January 5. A probable value for H_B is fixed at 12.70 m at 1800 h on January 4, based on the appearance of the stage hydrograph at Thamesville. Again, no measurements of h_i are available but the estimated value for this event is 15 cm.

At Kent Bridge, breakup was not initiated even though the stage reached an estimated peak of 177.49 m. The applicable h_i is estimated as 20 cm. Similarly, it is estimated that $H_B \geq 175.86$ m (January 5).

Third (main) Runoff Event. Due to freezing at high stages after the second event, new values of H_F need to be established for the third event. At Thamesville, where breakup had started and new ice cover formed, this can be obtained from Fig. 3, i.e., H_F = 12.28 m on January 15 (= peak daily average stage following the second runoff event). The value of H_B was in the range 14.84 m to 15.27 m (1908 h to 2045 h, March 13). The value of h_i was measured at 33 cm on March 9 (Table 1) and this is considered representative of breakup conditions.

At Kent Bridge and Sherman Brown Bridge, it is difficult to estimate the new H_F's. The weather turned cold on January 7 but stages remained well above the old H_F's for several days so that the open water strips at the sides would likely have frozen over. Using weather data and gauge records at Thamesville and Chatham it is, with considerable uncetainty, estimated that H_F = 176.45 m at Kent Bridge and H_F = 175.48 m at Sherman Brown Bridge. Corresponding values of breakup initiation levels are H_B = 179.88-180.13 m for Kent Bridge (1625h to 1940 h, March 16) and 178.38-178.69 m for Sherman Brown Bridge

(1100 h, March 17 to 0750, March 18). Respective ice thicknesses are etimated as 43 and 44 cm, using Table 1 and weather records.

The results of the above interpretation of breakup initiation events are summarized in Table 2.

In earlier reports (Beltaos 1981; 1983a) the few observational data available were utilized along with historical data at Thamesville to establish empirical and semi-empirical relationships that can be used to forecast the onset of breakup. These relationships may be stated as follows.

$$H_B - H_F \approx f_1(hi) \tag{1}$$

$$\frac{W_B}{W_i} \approx f_2\left(\frac{h_i}{W_i}\right) \tag{2}$$

in which W_B = water surface width at the stage H_B, and W_i = width of the winter ice cover. Eq. 1 is purely empirical whereas Eq. 2 derives from the conceptual model mentioned earlier. It is noted that both Eqs. 1 and 2 do not take into consideration the effects of thermal ice deterioration which, though generally important, does not seem to be a primary factor for the Thamesville gauge site. One reason may be that breakup at Thamesville is usually initiated after significant rainfall and quick rise of the water level so that thermal ice deterioration is usually moderate. Another reason is the fact that the historical data used so far exhibit large scatter, of which an unknown part is due to uncertainties inherent in analyzing past records (see, for example Beltaos 1984c).

In this report, the historical data are ignored, so as to minimize scatter caused by interpretational uncertainties. For convenience, the observational data accumulated to date are summarized in Tables 3, 4 and 5. Apart from symbols that have already been defined, W_F is the water surface width at the stage H_F and represents

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$$H_B = H = f_1(hi) \qquad (1)_F$$

$$\frac{W_B}{W_I} = f_2\left(\frac{h_i}{W_i}\right) \qquad (2)$$

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In this report, the historical data are ignored, so as to minimize scatter caused by interpretational uncertainties. For convenience, the observational data accumulated to date are summarized in Tables 3, 4 and 5. Apart from symbols that have already been defined, W_F is the water surface width at the stage H_F and represents

a first approximation for the width of the winter ice cover. However, as breakup is approached and the discharge begins to increase, uplift pressures develop under the ice which eventually causes longitudinal cracks to form. In the lower Thames River, cracks form near each shore so that the effective width of the ice cover, W_i, is equal to the distance between these cracks. The location of the side cracks can be approximately predicted via a structural analysis as explained elsewhere (Beltaos 1984d). In this manner, a correction can be applied to W_F in order to obtain an improved estimate of W_i (see Tables 3-5).

Using the data from Tables 3-5, (H_B-H_F) can be calculated and plotted against h_i, as suggested by the empirical relation (Eq. 1), in Fig. 13. In general, the data points scatter considerably, but a fairly good correlation exists for Thamesville, i.e.,

$$H_B - H_F \simeq 8\ h_i \quad \text{(Thamesville)} \tag{3}$$

For Kent Bridge and Sherman Brown Bridge, it is not possible as yet to draw any conclusions with regard to this type of correlation.

Figs. 14(a) and (b) show the data plotted in the dimensionless form of W_B/W_F versus $100\ h_i/W_F$ and W_B/W_i versus $100\ h_i/W_i$, respectively. Both of these graphs improve the correlation over Fig. 13 while use of the corrected width W_i seems to effect a further improvement over the use of W_F. The various widths used herein are reach-average values derived from several cross-sections near the respective sites.

The preceding considerations support the conceptual model developed by the writer earlier but there are several limitations, as summarized by Beltaos (1983a). One important limitation is manifested by the usual mode of breakup in the Thames River below Chatham. Here, the water level is strongly influenced by that of Lake St. Clair and stage increases of the magnitude required to initiate breakup according to the writer's model do not occur. Rather, the ice cover is destroyed by thermal effects and advancing ice jams that comprise broken ice from

upstream reaches. Here, an indicator of imminent breakup is the proximity of an ice jam upstream.

3.2 Ice Jams

Several major jams were observed and documented during the 1982 breakup. Water levels along these jams were obtained from photographic records. Supplementary hydrometric information (e.g., cross-sections, open-water slope, discharge) were obtained from open-water surveys and from WSC gauge records. Ice jam data obtained in this manner can be used to test/calibrate the existing theory, as described by Beltaos (1983c). This theory assumes the jam to be a floating granular mass and gives the aggregate thickness of the jam, t, that is necessary to resist the applied forces (Pariset et al 1966; Uzuner and Kenendy 1976). At the same time, the flow depth under the jam, y, can be related to the flow discharge (assuming negligible seepage through the jam voids), via a hydraulic resistance relationship. The overall water depth, H_j, is then given by (Beltaos 1983c):

$$\underbrace{\frac{H_j}{WS_w}}_{=\,y/WS_w}\ (\equiv\eta) = 0.63\, f_o^{1/3}\,\xi + \underbrace{\frac{5.75}{\mu}\left\{1+\sqrt{1+0.11\,\mu f_o^{1/3}\left(\frac{f_i}{f_o}\right)\xi}\right\}}_{t_s/WS_w} \qquad (4)$$

in which $H_j = y + t_s$; t_s = submerged portion of jam's thickness = $s_i t$ (for porosity of jam being the same above and below the water surface); s_i = specific gravity of ice, fixed at 0.92 herein; f_o = composite friction factor of the flow under the jam; f_i = friction factor of the jam's underside; μ = dimensionless coefficient that depends on the internal friction of the jam; W = channel width measured along the bottom of the jam; S_w = water surface slope; and ξ is a dimensionless discharge, defined by:

$$\xi \equiv (q^2/gS_w)^{1/3}/WS_w \qquad (5)$$

with q = discharge per unit width = Q/W; and g = acceleration due to gravity.

Earlier work (Beltaos 1983c, 1984a) has indicated that the main variable on the RHS of Eq. 4 is ξ. This was verified by plotting observed values of n versus ξ and obtaining a relationship exhibiting relatively little scatter. It is emphasized that the theory has been derived for the "equilibrium" reach of a jam, this being a region where the jam thickness and flow depth are relatively uniform. When interpreting field data, an indication of equilibrium conditions is approximate equality between the ice jam water surface slope, S_w, and the open-water slope in the same reach, S_o. This condition is realized frequently at uncontrolled river reaches but a significant portion of the lower Thames River is subject to effects from the level of Lake St. Clair. Here, the open-water slope changes with discharge and lake level (e.g., see Knowles and Hodgins 1980) and thus it is not always possible to use the above mentioned criterion for determining whether a jam is in equilibrium. Therefore, some of the present data can only be compared with equilibrium data on the assumption that Eq. 4 is approximately valid which requires that longitudinal gradients of jam thickness and flow depth be small. This is likely to be the case for the present jams, if attention is restricted to regions well upstream of the respective toes. However, it is difficult to show this rigorously without resorting to a numerical model of steady-state, non-equilibrium jams. Work is now in progress to develop such a model. With this background, the present ice jam observations are summarized next.

Jam near Fairfield Museum (Fig. 5). This jam formed sometime between 1500, March 13 and 0730, March 14, and was caused by large ice sheets lodged against the river banks. Photos for water level profiles were obtained twice, at about 1400, March 14 and 1500 March 16. At 1505 on March 16, a large section of the jam moved out while the remaining section released before 0830, March 17. The jam was originally 700 m long, starting at 76.43 and ending at 75.72 km*. The available water level data are not accurate enough and the jam was too short to enable reliable determinination of S_w (Fig. 15). Using cross-sectional data at 75.37, 75.72 and 76.07 km and assuming equilibrium conditions, i.e., S_w = 0.30 m/km (= open-water slope in jammed reach), it is estimated that: Q = 250 m^3/s, W = 53.1 m; H_j = 5.6 m, ξ = 1230, n = 353 on March 14; and Q = 320 m^3/s, W = 53.7 m, H_j = 5.7 m, ξ = 1425, n = 356 on March 16.

Jam at Kent Bridge (Fig. 6). This jam formed sometime between 1625, March 16 and 1300, March 17. The toe was at Kent Bridge (50.02 km) and the head about 1.8 km upstream. The jam was caused by a few large ice sheets lodged against the bridge piers and the bend upstream of the bridge. Due to access difficulties, the water level profile was not documented. The jam released at 1025, March 19.

Jam near Louisville (Fig. 9). This jam was first noticed at 1630, March 18 and water levels were photographed 30 minutes later. Jamming was caused by the presence of undisturbed ice cover and a nearby sharp bend. The jam was 1500 m long, starting at 41.15 and ending at 42.65 km. At the time of the photographic survey, the discharge is estimated to have been about 427 m^3/s, reaching a peak of 445 m^3/s at about midnight of March 18. This may have caused the jam to release as it was no longer there at 0710, March 19.

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* All locations designated in this manner represent river distance upstream of the mouth.

The water level profile along this jam is shown in Fig. 16 where the straight line drawn through the data points has a slope of 0.3 m/km. Using this slope and cross-sectional data at 41.59, 42.00 and 42.40 km, gives W = 75.5 m, H_j = 6.3 m, ξ = 1000 and η = 284.

Jam downstream of Kent Bridge (Fig. 11). This jam formed shortly before 1052 on March 19 when the ice run resulting from the release of the Kent Bridge jam (1025, March 19) was arrested by the lodging of a large ice sheet at a sharp bend. The jam was documented at about 1330 and released shortly afterwards. The water level profile along this jam is shown in Fig. 17 where a slope of 0.29 m/km is indicated along the main portion of the jam. Using Q ≡ 425 m^3/s and cross-sectional data at 48.65, 49.15 and 49.86 km, it is found that H_j = 6.6 m, W = 83.8 m, ξ = 855 and η = 270.

Jam near Prairie Siding (Fig. 12). This jam formed against undisturbed ice cover at about 1600, March 19, and was documented two hours later. At about 1630, flooding began on the right bank. The jam released at 1400, March 20, after considerable activity downstream of the toe and formation of open leads. The water level profile along the jam is shown in Fig. 18, indicating a slope of 0.40 m/km, as opposed to an almost horizontal open-water surface, owing to the proximity of Lake St. Clair. Using Q = 435 m^3/s and cross-sectional data at 12.82, 13.30, 13.78 and 14.31 km, we find H_j = 6.1 m, W = 119 m, ξ = 318 and η = 126.

The above descriptions and data on the various ice jams are summarized in Tables 6 and 7. Fig. 19 shows the data plotted in the form of η versus ξ, along with data available from previous case studies on equilibrium jams. The latter data set includes: data summarized by Beltaos (1983c); two recent case studies in the Peace and Mackenzie Rivers reported by Neill and Andres (1984) and Rivard et al (1984), respectively; previous Thames River data by Beltaos (1981), (1983a); and data from the upper Grand River (Wong and Beltaos 1983). Data points

joined by horizontal line segments represent instances of uncertainty with respect to discharge, whereby ξ is only known as a range. Numerous Canadian rivers are represented in Fig. 19 with considerable variation in stream magnitude, i.e., W = 36 to 1750 m and Q = 10 to 14,700 m^3/s. Thus, the consistency exhibited by the data points in Fig. 19 provides strong support for the existing theory of ice jams and the resulting η-ξ relationship. At the same time, the present data points seem to be compatible with the equilibrium ones which suggests that a condition of approximate equilibrium is at least attained by the Thames River jams in the lake-influenced reaches.

3.3 Release of Ice Jams - Peak Breakup Stages

The peak breakup stage at a given location is usually caused by a nearby jam and is thus governed by the peak flow discharge attained during the jam's presence. Therefore, the mechanism of ice jam release is an important factor influencing the peak stage during breakup. The conceptual model of breakup described earlier has an interesting consequence in this regard, as follows. It has been postulated that breakup is initiated when some of the large ice sheets that form by transverse cracking are able to clear various obstacles and start to move downstream. Pursuing this concept further, it is reasonable to expect that major jams form behind those ice sheets that are least amenable to dislodgement and they release when these sheets are able to move. Then, by a similar reasoning as that leading to Eq. 2, one could write:

$$\frac{W_R}{W_i} \leq f_3 \left(\frac{h_i}{W_i}\right) \qquad (6)$$

in which W_R = channel width at the stage of release. The inequality sign accounts for the fact that, during the breakup period, the ice

sheets responsible for jams will be subjected to reductions in competence and dimensions owing to thermal and mechanical deterioration. For given channel geometry, slope and resistance characteristics, one could estimate the discharge Q_R that corresponds to W_R, by taking into account partial coverage by sheet ice. The nearby peak breakup stage should then not exceed that of an equilibrium jam with discharge Q_R (see Fig. 19). Recalling Eq. 6 shows that Q_R would depend on freeze up conditions and ice competence. This reasoning was confirmed by an indirect analysis for the Thamesville reach in a previous report (Beltaos 1983) using historical gauge data. Herein, a more direct test of Eq. 6 can be performed using available data on observed ice jam releases (summarized in Table 8). From cross-sections surveyed at or near the toes of the various ice jams, local values of W_R and W_i can be estimated. For W_i, corresponding ice thicknesses and freeze up stages were obtained by interpolation in cases where toe locations did not coincide with routine stage-measuring sites. Figure 20 shows the available data plotted in the form suggested by Eq. 6 where an upper envelope consistent with expectation is indicated.

It is noted that Fig. 20 only includes data pertaining to jams located above Chatham where the model leading to Eq. 6 applies. As mentioned earlier, the pattern of breakup downstream of Chatham differs from this model owing to strong lake effects. Here, breakup involves destruction of the winter ice cover by intermittently advancing jams, aided by thermal effects. It is difficult to define a firm boundary between these two reaches. The former type of breakup that is consistent with the model of Eqs. 2 and 6 has been observed to occur as far downstream as Chatham. The latter type has been observed near the river mouth and as far upstream as the vicinity of the Yacht Club. In this reach, breakup comprises a sequence of releases and reformations of an ice jam that is initially of minor size but generally lengthens as it advances. The releases of this jam are usually preceded by the appearance of large open leads in the sheet ice cover immediately downstream of the toe. The mechanism of release in this case is unknown

and thus it is not possible at present to formulate a release criterion such as that of Fig. 20.

4.0 DISCUSSION

The third year's ice observations in the lower Thames River have been described and analyzed in the previous sections. The 1982 breakup was similar to the previous one, occurring under conditions of relatively thick ice cover and intense runoff. However, flooding in 1982 was minor compared to that of 1981. The reason for this occurrence is not known at this time but the following factors might be relevant: (a) lower 1982 discharges (peak in 1982 = 450 m^3/s; peak in 1981 = 630 m^3/s); (b) ice breaking operations performed in 1982 but not in 1981; and (c) 1982 breakup occurring in March, as opposed to February for 1981, which would result in greater thermal deterioration of the ice in 1982 due to increased short wave radiation.

While it is still early for generalizations, a pattern of breakup is beginning to emerge, based on the three years' observations performed to date. Within the study reach, breakup is first initiated near Fairfield Museum and Thamesville, and subsequently appears to advance downstream. However through and below Chatham, breakup develops independently of upstream ice conditions. It is common to find substantial river sections that are ice covered upstream of Chatham while, at the same time, the river is clear through Chatham and downstream to near Prairie Siding. Eventually the ice upstream of Chatham releases and joins the downstream ice jam. The combined jam is only a few kilometres long which suggests intense melting and possibly ice transport under the jam.

Quantitative interpretation of the 1982 observations focussed on two major aspects, i.e., breakup initiation and ice jams. The data accumulated to date support the writer's conceptual model of breakup, at least as far downstream as Chatham. This model was confirmed more

directly in 1982 by the observed pattern of transverse cracks. Data on releases of ice jams that form upstream of Chatham are also consistent with this concept.

Downstream of Chatham, the pattern of breakup differs from and is more complex than that upstream, owing to lake effects. Here, breakup consists of intermittent movements of an ice jam that is eventually joined by broken ice from upstream. A governing factor is the mechanism of release but, to date, it remains little understood.

The 1982 data on ice jam stages are consistent with the $\eta - \xi$ relationship that relates dimensionless water depth to dimensionless discharge via the jam stability equation and hydraulic resistance considerations. This suggests that the lower Thames jams attain a condition of at least approximate equilibrium. For analytical predictions of jam stages, the graph of Fig. 19 can thus be used in conjunction with cross-sectional data applicable to the reach of interest. However, selection of suitable values of the slope, S_w, requires reference to past experience because S_w may depend on location, discharge, jam length and lake level. A preferable alternative would be to use a numerical model whereby longitudinal variations of flow depth and jam thickness would be accounted for and slope would be computed as part of the model output. Work is now in progress to develop such a model (see also Beltaos and Wong 1984). In the meantime, use of the data now available in conjunction with Fig. 19 indicates that flooding may be experienced near the river mouth* with discharges in excess of about 400 m^3/s and jams of the usual configuration. Whether a jam can remain stable at this or higher discharge values may depend on the thickness of the winter ice cover and thermal deterioration effects. For example, the 1980 jam at the mouth released at a discharge of about 200 m^3/s under conditions of relatively thin ice cover and substantial thermal effects. While the incoming discharge

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* a highly vulnerable section of the river in terms of flood risk and resulting damages.

continued to increase, the flow reverted to an open-water condition and no flooding occurred. Clearly, the question of ice jam stability and release in the lower portion of the study reach requires additional study.

5.0 SUMMARY AND CONCLUSIONS

The 1982 breakup in the lower Thames River resulted in moderate flooding that again occurred well downstream of Chatham. Major differences from the 1981 breakup that caused serious flooding were in flow discharge, time of year (March 1982 as opposed to February 1981) and ice breaking that was carried out in 1982.

The breakup pattern observed to date suggests a subdivision of the study reach into two subreaches (Bothwell to Chatham and Chatham to mouth). In the first subreach, breakup appears to advance in the downstream direction and to be triggered by a rise in water level that allows various ice sheets to clear respective obstacles. In the second subreach, breakup also advances in the downstream direction but is now triggered by thermal deterioration and mechanical destruction associated with an intermittently advancing ice jam.

The 1982 ice jam measurements adhere to a dimensionless depth-discharge relationship that has been developed earlier based on the theory of equilibrium jams and resistance considerations.

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TABLES

TABLE 1. Ice Thickness Measurements, Winter 1981-82.

Location	Average h_i (cm)/Number of Measurements							
	Jan.18	Jan.20	Jan.21	Feb.2	Feb.4	Feb.15	Feb.22	Mar 9
Lighthouse dock[1]	32.4/6					48.7/3	46.0/5	
Gov't dock[1]	26.7/6			38.9/6		40.0/2	46.2/5	
Jeannettes Ck[1]	29.5/4			38.6/4		48.3/1	48.3/2	
3.44 km[2]		27.4/15						
14.31 km (Prairie Siding)[1]	30.4/8			41.4/8		43.2/1	39.4/3	
17.45 km			29.3/12					
18.80 km			29.0/11					
20.10 km			28.5/12					
≈29.5 km (Chatham - 4th St)[1]	24.6/3			34.7/3		41.3/2	43.2/3	
38.56 km					36.6/7			
39.19 km					35.8/9			
40.69 km					29.9/9			
41.59 km					36.7/9			
42.77 km				32.2/8				
43.53 km				37.5/10				
44.59 km				36.3/8				
48.01 km				43.4/8				
50.01 km (Kent B)[1]						45.7/1		
65.55 km (Thamesville Bridge)[3]				32.3/16		35.6/1		33.4/17

(1) Provided by Lower Thames Valley Conservation Authority.
(2) River distance above mouth.
(3) Provided by Water Survey of Canada - Guelph office.

TABLE 2. Summary of Breakup Initiation Data, 1981-82 Season

Location	H_F / date	H_B(m) / time and date	h_i (cm)	Accuracy of h_i	Remarks
Thamesville (WSC gauge)	11.48 / Dec. 19	>12.36 / 2000, Dec. 24	12	Est'd from weather conditions and past years' experience	H's are gauge heights; add 167.56 m to find geodetic elevations. Peak stage during event = 12.36 m, 2000; Dec. 24
	11.48 / Dec. 19	12.70(probable) / 1800, Jan. 4 and <13.62 / 1200, Jan. 5	15	Est'd from weather conditions and past years' experience	Peak stage during event = 13.62 m, 1200, Jan. 5.
	12.28 / Jan. 15	14.84 - 15.27 / 1908-2045, Mar.13	33	From measurements	Peak stage during event = 17.96 m, 0500, Mar. 19
Kent Bridge	175.61 / Dec. 19	>176.43 / ≈0100, Dec. 25	15	Estimated as above	H's are geodetic elevation; estimated from previously established correlation with Thamesville Stage under ice conditions.
	175.61 / Dec. 19	>177.49 / ≈1700, Jan. 5	20	Estimated as above	
	176.45(?) / Jan. 9	179.88-180.13 / 1625-1940, Mar.16	43	From measurements	H_F is uncertain. Peak stage during event ≈ 182.45 m, 1318, Mar. 19.
Sherman Brown Bridge	175.16 / Dec. 18	>175.26 / p.m., Dec. 26	Unknown	N.A.	H's are geodetic elevations.
	175.16 / Dec. 18	>175.86 / p.m., Jan. 5	Unknown	N.A.	
	175.48(?) / Jan. 9	178.38-178.69 / 1100 Mar.17-0750 Mar.18	44	From measurements	H_F is uncertain. Peak stage during event ≈ 179.67, 0800 Mar. 19

TABLE 3. Breakup Initiation Data From Observations - Thames River at Thamesville

Season	H_F (m)	H_B (m)	h_i (cm)	W_F (m)	W_i (m)	W_B (m)
1979-80	12.40	13.40	12*	39.7	35.0	44.3
1979-80	12.05	13.26	18	38.1	31.7	43.7
1980-81	12.15	14.60	31	38.6	28.9	50.5
1981-82	11.48	>12.36	12*	35.5	30.8	>39.5
1981-82	11.48	12.70*	15*	35.5	29.9	41.1*
1981-82	12.28	14.84 - 15.27	33	39.2	29.0	51.7 - 53.3

* Estimated or uncertain data

TABLE 4. Breakup Initiation Data From Observations - Thames River at Kent Bridge

Season	H_F (m)	H_B (m)	h_i (cm)	W_F (m)	W_i (m)	W_B (m)
1979-80	176.18	177.23	20	50.0	43.1	55.9
1980-81	176.28	178.88	32	50.4	40.5	68.0
1981-82	175.61	>176.43*	15*	47.2	41.6*	>51.1
1982-82	175.61	>177.49*	20*	47.2	40.3*	>58.0
1981-82	176.45*	179.88 - 180.13	43	51.2	38.9	78.5 - 80.5

* Estimated or uncertain data

TABLE 5. Breakup Initiation Data From Observations - Thames River at Sherman Brown Bridge

Season	H_F (m)	H_B (m)	h_i (cm)	W_F (m)	W_i (m)	W_B (m)
1979-80	175.77*	176.53	21*	71.5	64.3*	74.5
1980-81	175.30	178.28	35	69.1	58.6	81.5
1981-82	175.48*	178.38 - 178.69	44	70.1*	57.6*	82.0 - 83.6

* Estimated or uncertain data

TABLE 6. Major Ice Jams During the March 1982 Breakup

Location Distances are km above river mouth		Time of Formation	Time of Release	Approximate Flow Discharge	Probable Causes
Toe	Head				
75.7 (near Fairfield Museum)	76.4	Between 1500 Mar. 13 and 0730 Mar. 14	1505, Mar. 16 - partial release; full release before 0830, Mar. 17	320 m^3/s at time of first release	A few large ice sheets lodged against the river banks
Kent Bridge (50.0 km)	51.8	Between 1625, Mar. 16 and 1300 Mar. 17	1025 Mar. 19	430 m^3/s at time of release	Large ice sheets lodged against bridge piers and bend upstream of bridge
47.9 (downstream of Kent Bridge)	49.8	Shortly before 1050, Mar. 19	1343, Mar. 19	420 m^3/s at time of release	Large ice sheet lodged at sharp bend
41.2 (near Louisville)	42.7	Before 1630, Mar. 18	Before 0710, Mar. 19	430 m^3/s at 1700 Mar. 18 [peak of 445 m^3/s at 2400 Mar. 17]	Ice cover and sharp bend
11.9 (near Prairie Siding)	14.9	Approx. 1600, Mar. 19	1400 Mar. 20	435 m^3/s at 1800 Mar. 19; 405 m^3/s at time of release	Ice cover

TABLE 7. Selected Ice Jam Characteristics: Thames River 1982

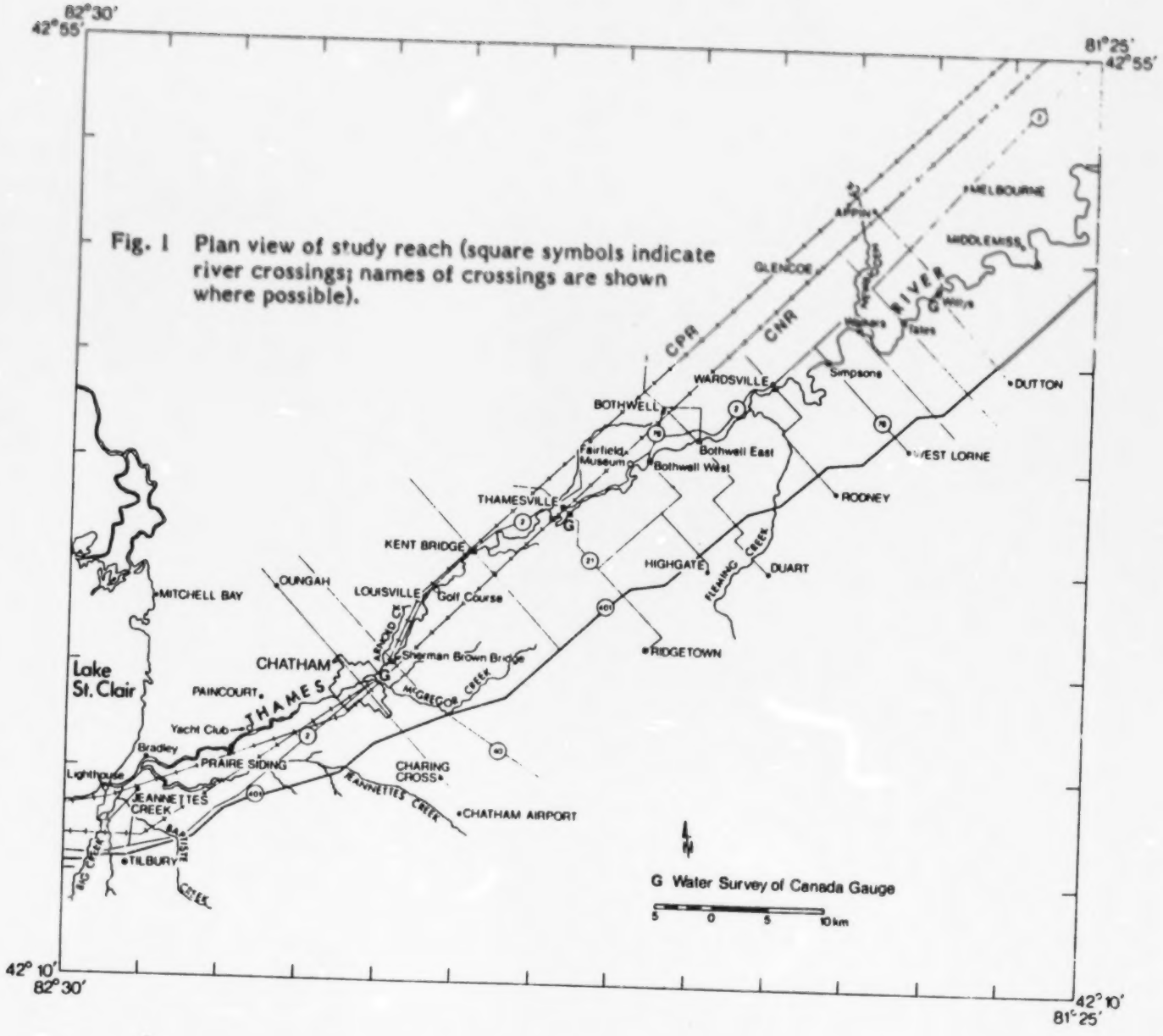
Approximate Location of Jam	Time	Q (m^3 S)	S (m/km)	h_T (m)	W (m)	ξ	n	Accuracy of Water Level Profile
Fairfield Museum	1400 Mar 14	250	0.30	5.6	53	1230	353	Poor
Fairfield Museum	1500 Mar 16	320	0.30	5.7	54	1425	356	Poor
Louisville	1700 Mar 18	430	0.30	6.3	76	1000	284	Fair
Kent Bridge (downstream)	1330 Mar 19	423	0.29	6.6	84	855	270	Fair
Prairie Siding	1800 Mar 19	435	0.40	6.1	119	318	126	Good

TABLE 8. Summary of Available Data on Ice Jam Releases

Jam Location	Date	Approx. h_i (1) (cm)	Approx. W_F (m)	Approx. W_i (m)	Approx. W_R (m)	Approx. Q_R (m^3/s)	Remarks
Mouth; L.St. Clair to 1.4 km	20.03.80	25	NA	NA	NA	200	No flooding
Sherman Brown Bridge; 33.8 to 40.5 km	19.03.80	21	63	56	67	200	No flooding
Near Golf Course;exact location unknown	19.03.80	20	-	-	-	180	No flooding
Kent Bridge; 50 to 51.5 km	18.03.80	20	52	45	63	150	No flooding
Near Fairfield Museum toe - unknown, head at 75.9 km	18.03.80	18	-	-	-	130	No flooding
Mouth; L. St. Clair to 1.9 km	23.02.81	45	NA	NA	NA	<550	Serious flooding
Near Mouth; 0.6 to 4.5 km	22.02.81	45	NA	NA	NA	<500	Moderate flooding
Near Yacht Club; 17.5 to 19.4 km	21.02.81	40	NA	NA	NA	350	No flooding
Near Louisville; 38.7 to 44.4 km	22.02.81	34	64	54	80-85	540	Moderate flooding
Near Golf Course; 43.5 to 48.5 km	20.02.81	33	63	53	85	300	No flooding
Kent Bridge; 50 to 53.2 km	20.02.81	32	54	44	79	260	No flooding
Fairfield Museum; 75.4 to 76.0 km	19.02.81	31	29	19	48	200	No flooding
Mouth, extent unknown	22.03.82	40	NA	NA	NA	350	Moderate flooding
Prairie Siding; 11.9 to 14.9 km	20.03.82	40	NA	NA	NA	405	Moderate flooding, disharge peaked at 435 m^3/s four hours prior to release.
Near Louisville 41.2 to 42.7 km	18.03.82	43	52	40	78	445	Minor flooding
Downstream of Kent Br. 47.9 to 49.8 km	19.03.82	43	65	53	96	420	No flooding
Kent Bridge; 50 to 51.8 km	19.03.82	43	53	41	88	430	No flooding
Fairfield Museum	16.03.82	33	37	27	62	320	No flooding

(1) Values apply to start of mild weather spell leading to breakup; thermal reductions in thickness are ignored.

FIGURES


82°30'
42°55'
81°25'
42°55'
Fig. 1 Plan view of study reach (square symbols indicate river crossings; names of crossings are shown where possible).
CPR
CNR
WARDSVILLE
BOTHWELL
Fairfield Museum
Bothwell East
Bothwell West
THAMESVILLE
KENT BRIDGE
OUNGAH
LOUISVILLE
Golf Course
MITCHELL BAY
CHATHAM
Sherman Brown Bridge
McGREGOR CREEK
PAINCOURT
Lake St. Clair
THAMES
Yacht Club
Bradley
Lighthouse
PRAIRIE SIDING
JEANNETTES CREEK
CHARING CROSS
CHATHAM AIRPORT
TILBURY
HIGHGATE
DUART
FLEMING CREEK
RIDGETOWN
ROONEY
WEST LORNE
DUTTON
Simpsons
MELBOURNE
MIDDLEMISS
GLENCOE
G Water Survey of Canada Gauge
5 0 5 10 km
42° 10'
82° 30'
42° 10'
81° 25'

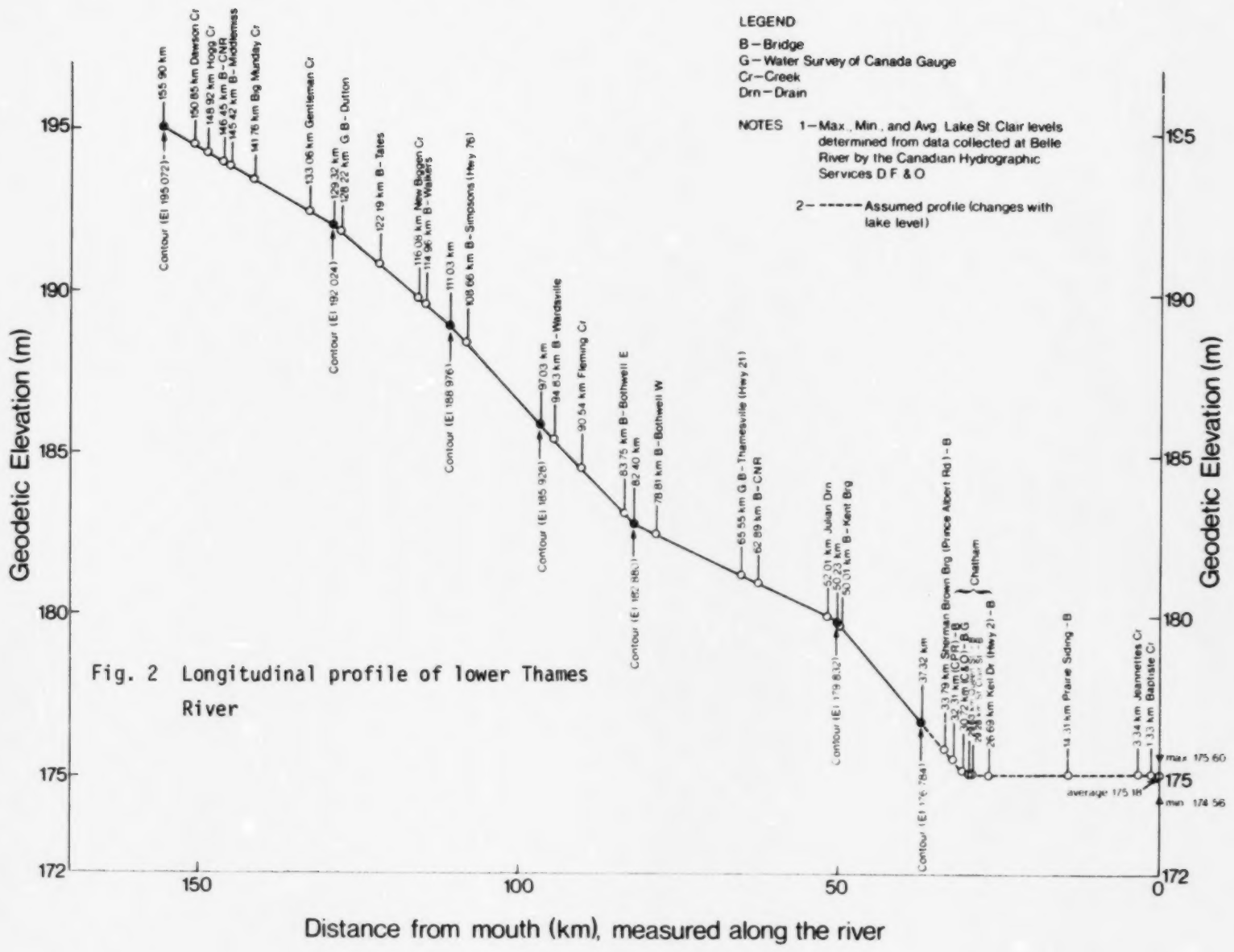

LEGEND
B – Bridge
G – Water Survey of Canada Gauge
Cr – Creek
Drn – Drain
NOTES 1 – Max., Min., and Avg. Lake St Clair levels determined from data collected at Belle River by the Canadian Hydrographic Services D F & O
2 – ------ Assumed profile (changes with lake level)
Geodetic Elevation (m)
Distance from mouth (km), measured along the river
155.90 km
150.85 km Dawson Cr
148.92 km Hogg Cr
146.45 km B – CNR
145.42 km B – Middlemess
141.76 km Big Muddy Cr
133.06 km Gentleman Cr
129.32 km
128.22 km G B – Dutton
122.19 km B – Tates
116.06 km New Boggen Cr
114.96 km B – Walkers
111.03 km
108.66 km B – Simpsons (Hwy 76)
97.03 km
94.83 km B – Wardsville
90.54 km Fleming Cr
83.75 km B – Bothwell E
82.40 km
78.81 km B – Bothwell W
65.55 km G B – Thamesville (Hwy 21)
62.89 km B – CNR
52.01 km Julian Drn
50.23 km
50.01 km B – Kent Brg
37.32 km
33.79 km Sherman Brown Brg (Prince Albert Rd) – B
Chatham
26.69 km Keil Dr (Hwy 21) – B
14.31 km Prairie Siding – B
3.34 km Jeannettes Cr
1.33 km Baptiste Cr
max 175.60
average 175.18
min 174.56
Contour (El 195.072)
Contour (El 192.024)
Contour (El 188.976)
Contour (El 185.928)
Contour (El 182.880)
Contour (El 179.832)
Contour (El 176.784)
195
190
185
180
175
172
150
100
50
0

Fig. 2 Longitudinal profile of lower Thames River

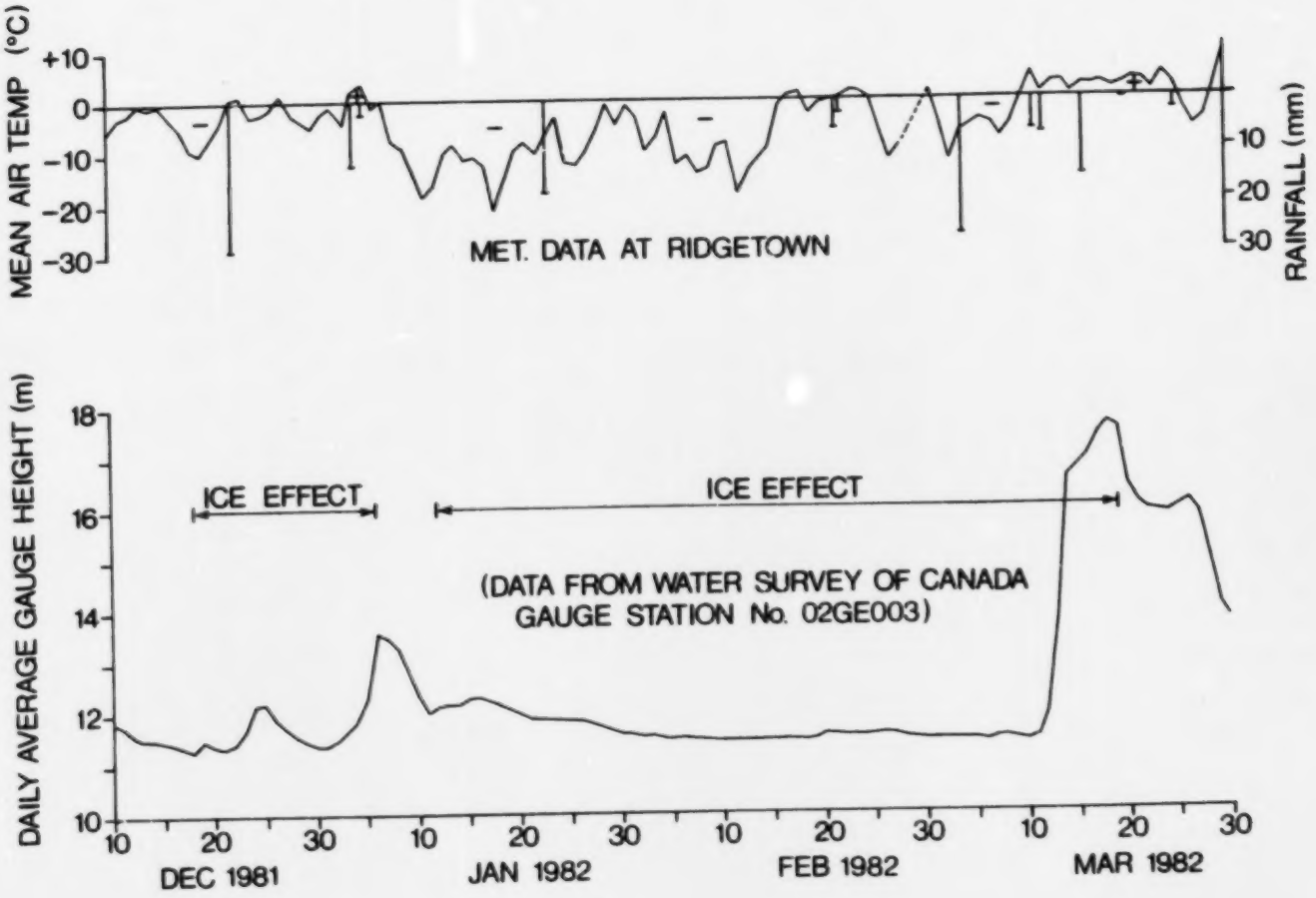


Fig. 3. Meteorological data and water levels near Thamesville.

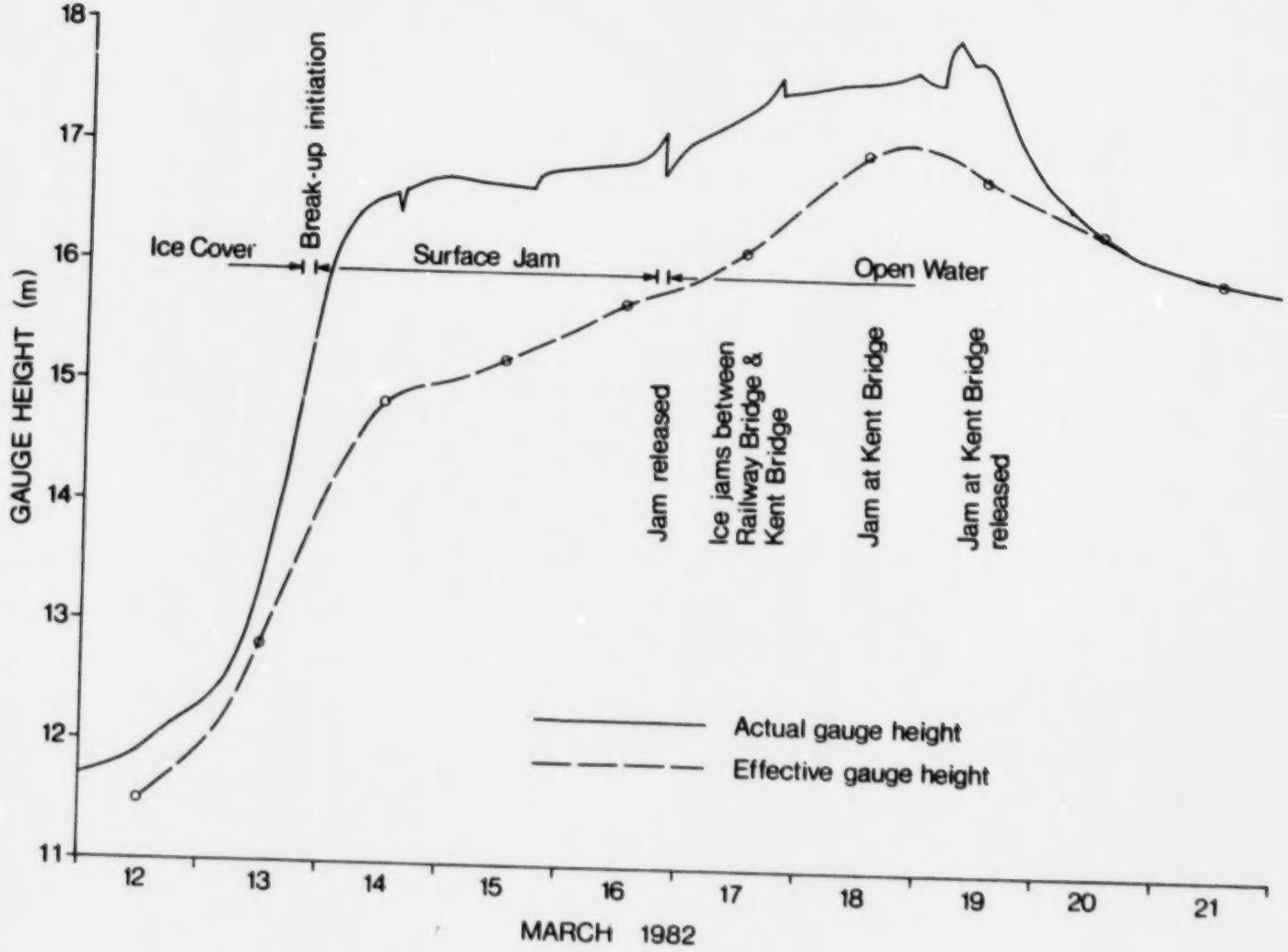


Fig. 4. Variation of stage at Thamesville during the breakup period; effective gauge height = gauge height for same discharge under open water conditions.

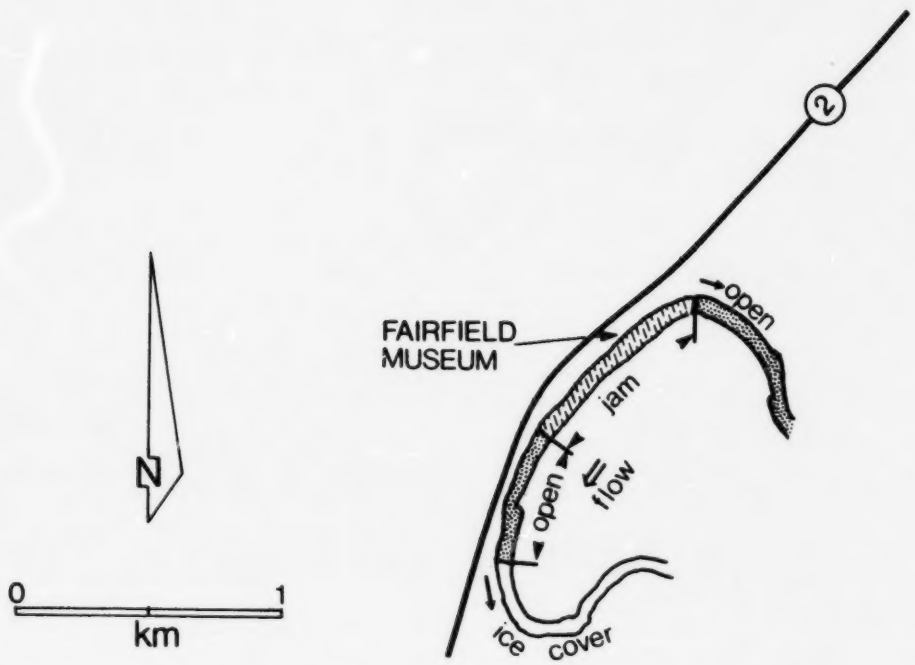


Fig. 5. Jam near Fairfield Museum, March 14, 1982.

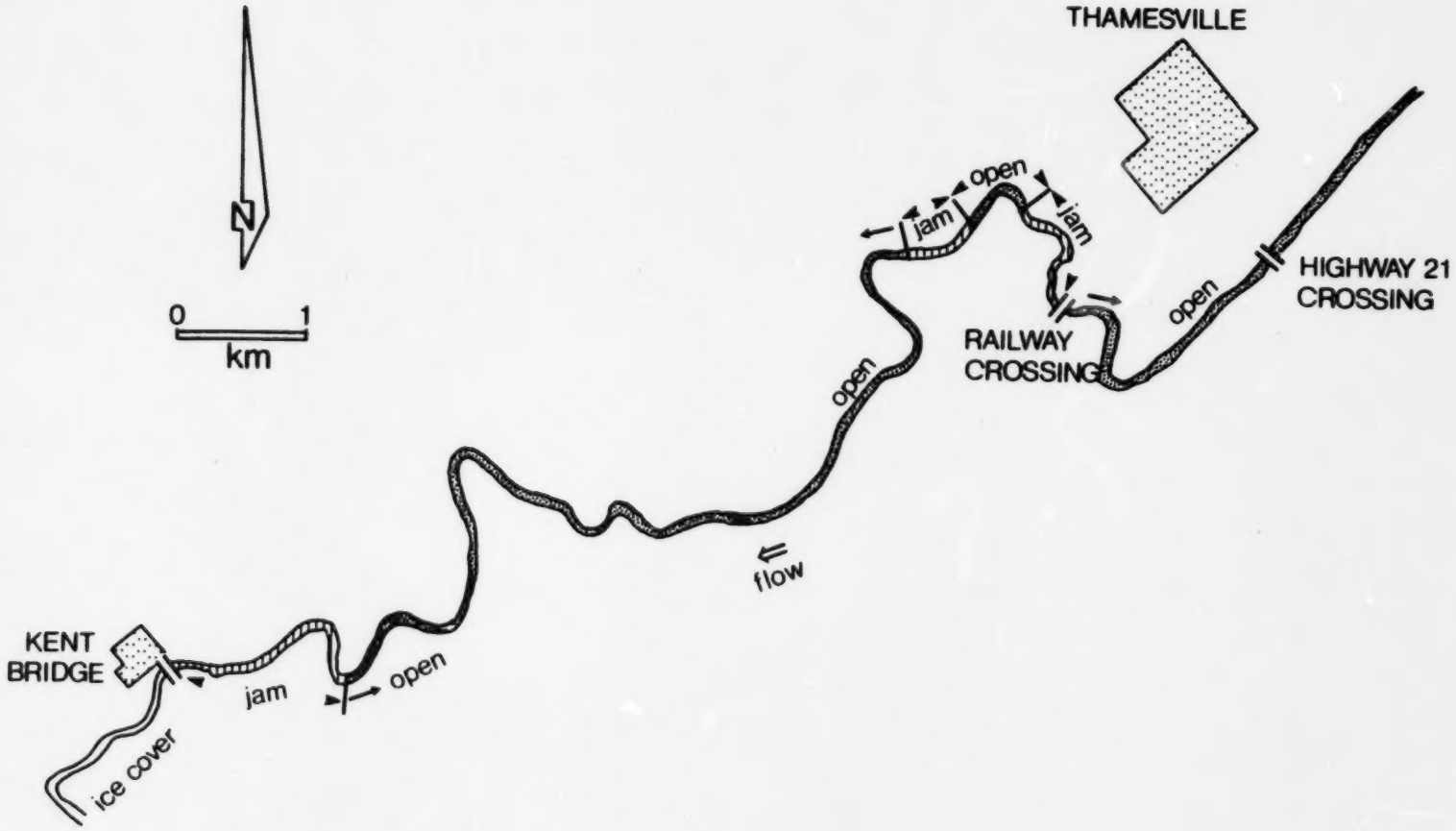


Fig. 6. Ice conditions near Thamesville and Kent Bridge, 1230 - 1340, March 17, 1982.

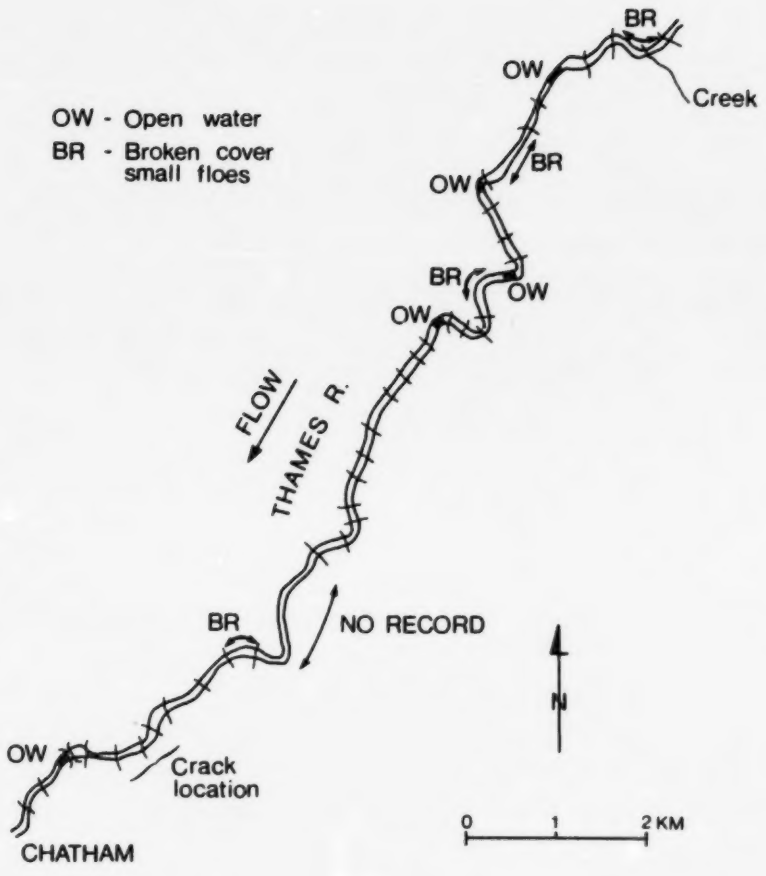


Fig. 7. Ice conditions and transverse crack locations, 1230 - 1340, March 17, 1982.

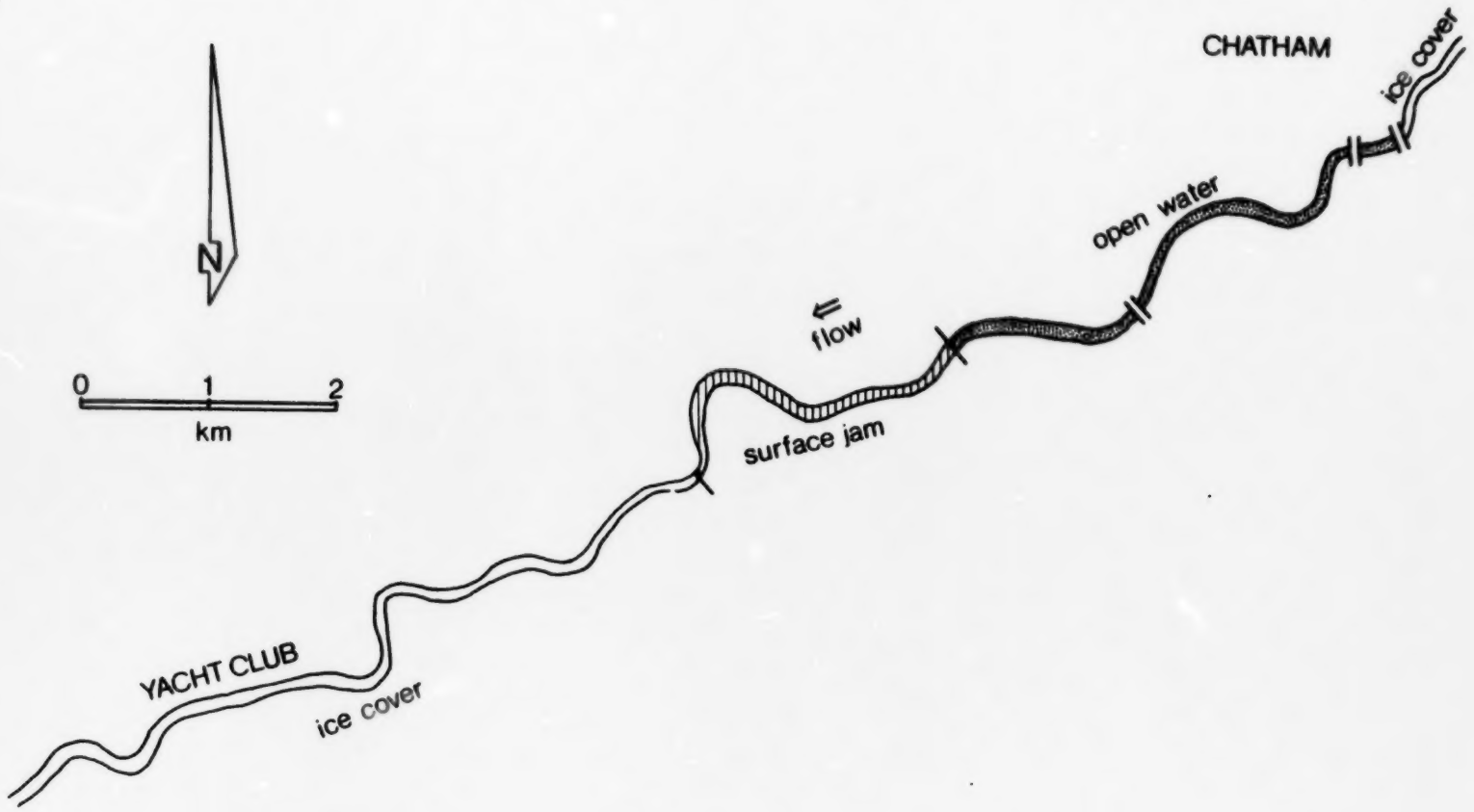


Fig. 8. Ice conditions near Chatham, 1230 - 1340, March 17, 1982.

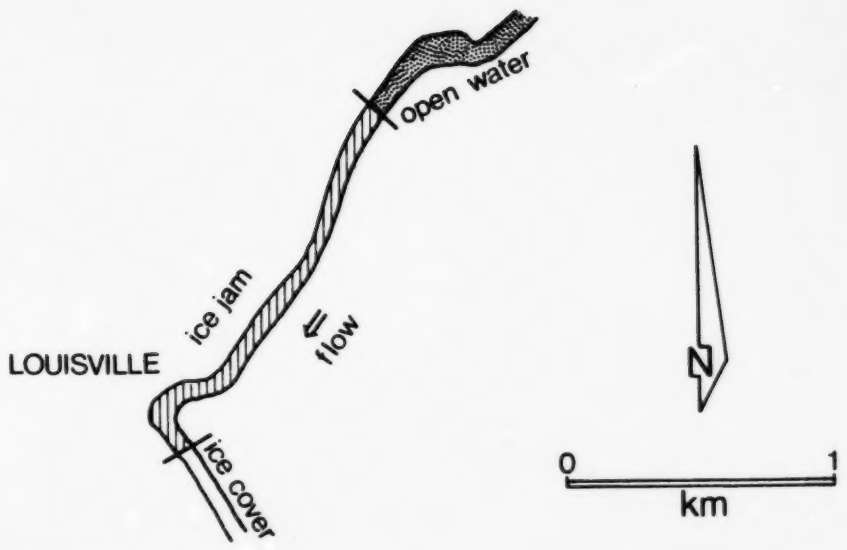


Fig. 9. Jam near Louisville, 1630 - 1750, March 18, 1982.

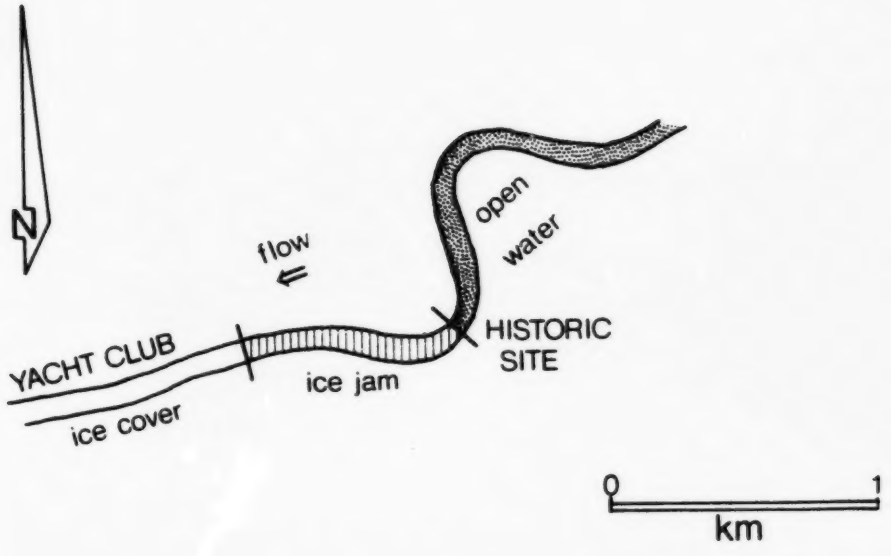


Fig. 10. Jam below Chatham, 1205, March 18, 1982.

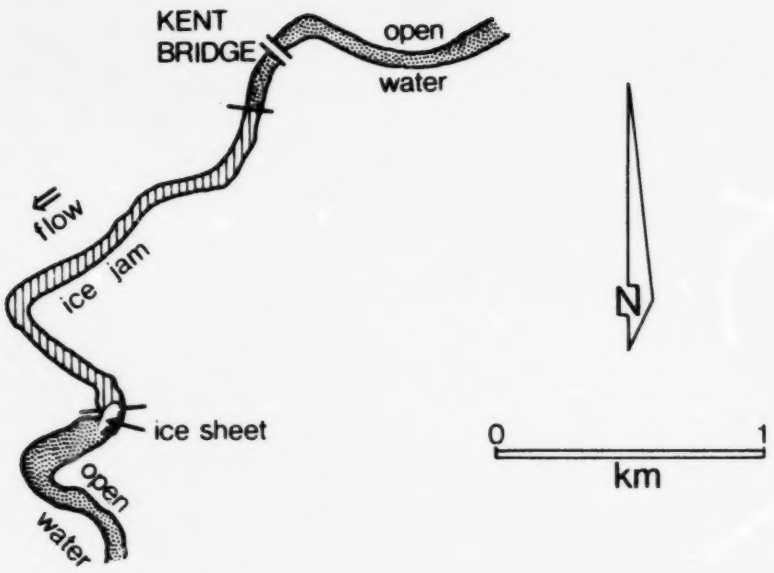


Fig. 11. Jam below Kent Bridge, 1320 - 1340, March 19, 1982.

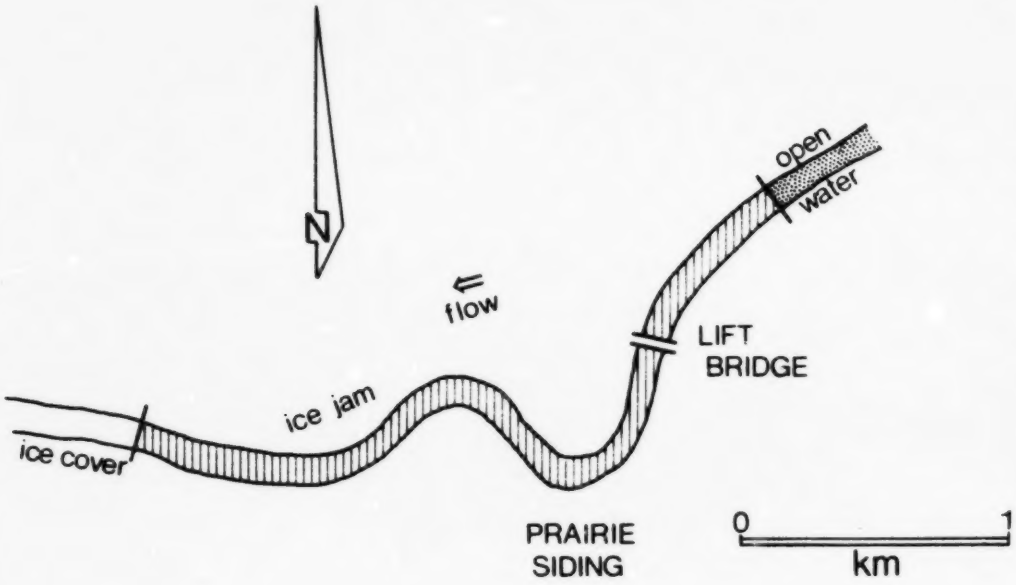


Fig. 12. Jam near Prairie Siding, 1800 - 1820, March 19, 1982.

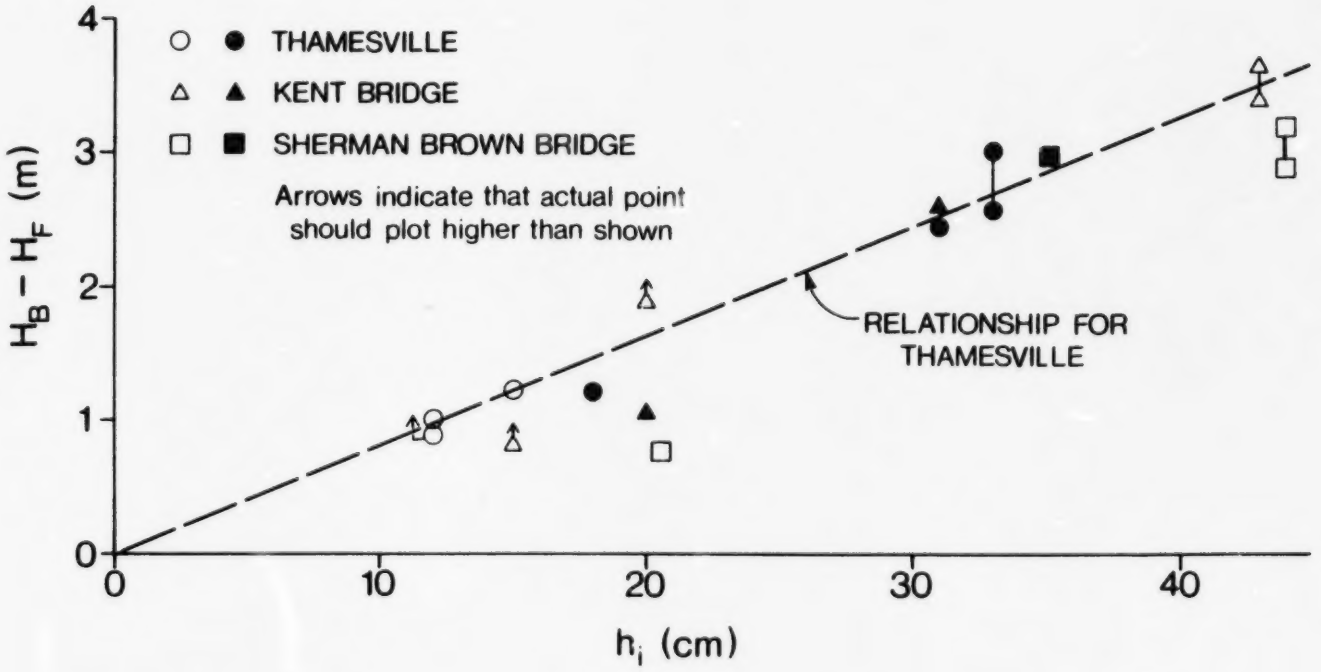


Fig. 13. Plot of $H_B - H_F$ versus ice thickness at three sites; open symbols denote uncertain data.

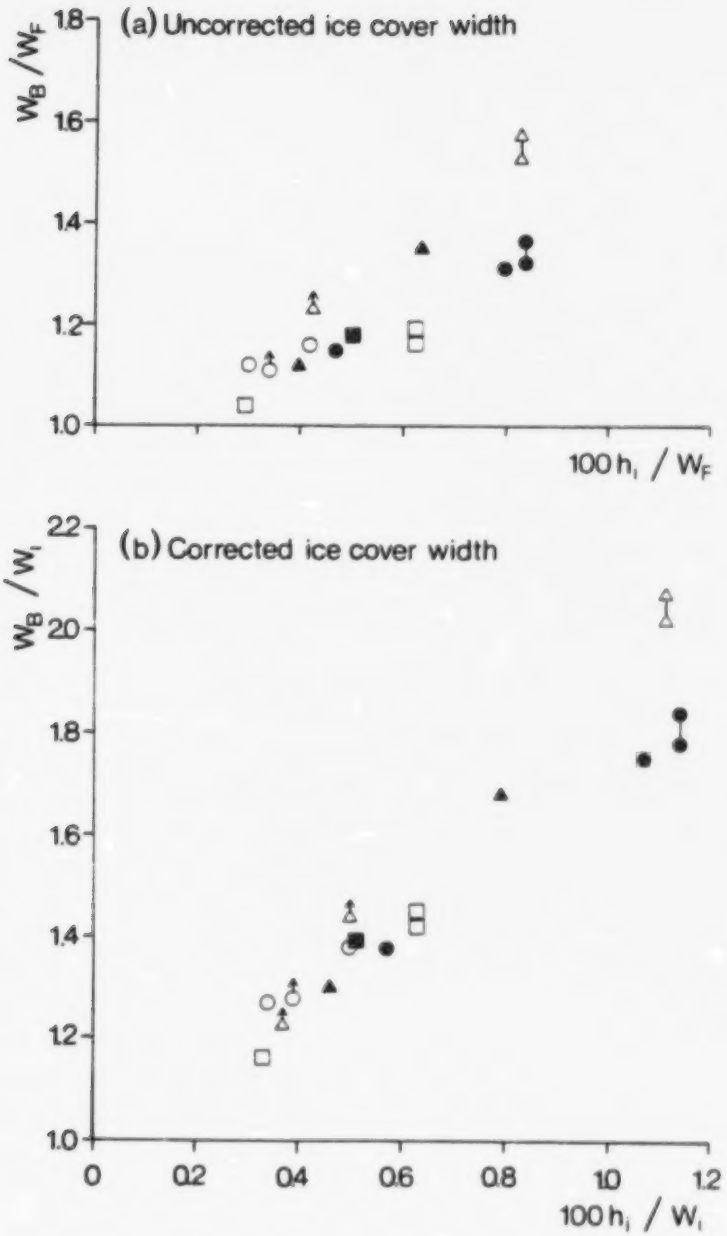


Fig. 14. Dimensionless breakup initiation relationships at three sites; legend same as for Figure 13.

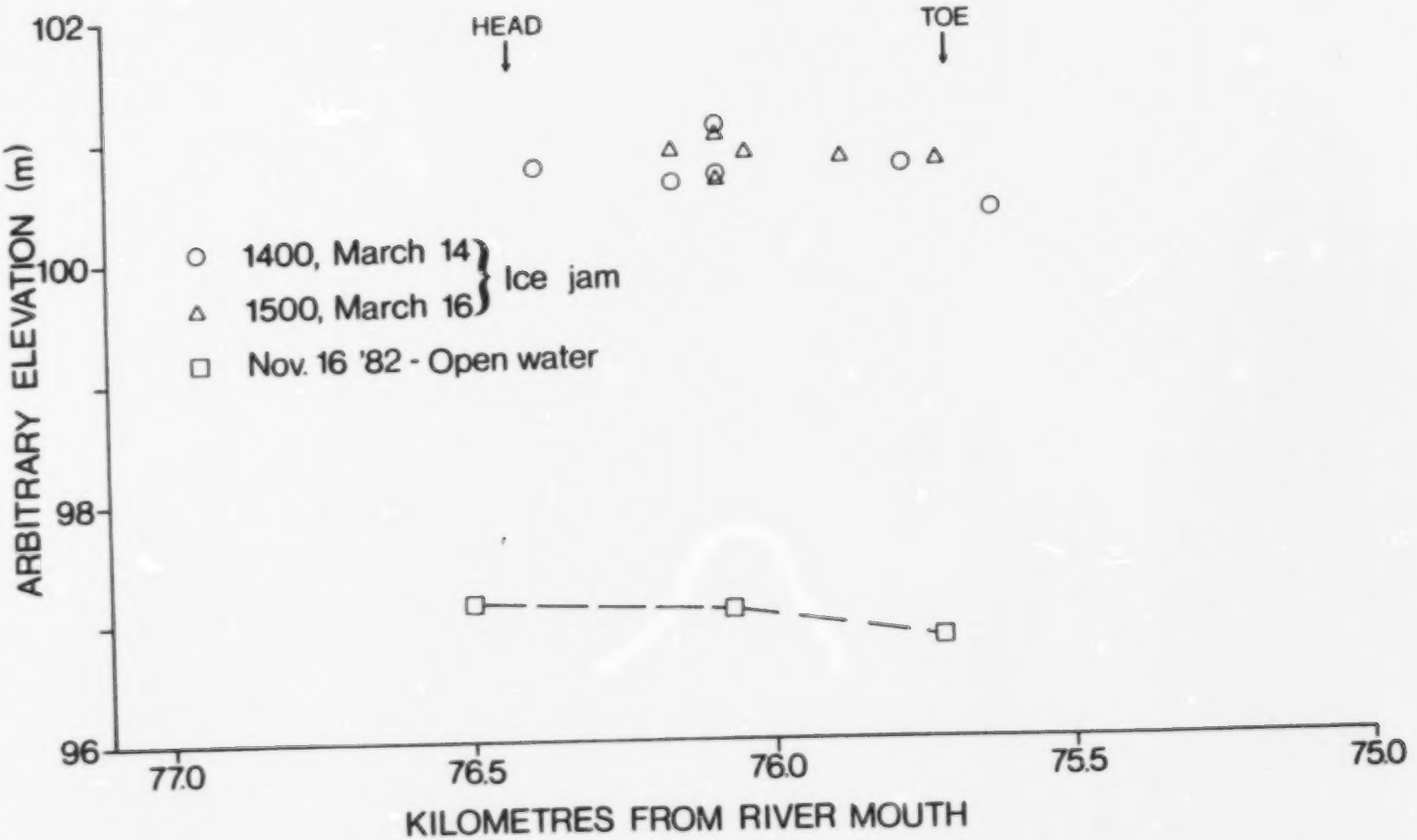


Fig. 15. Profiles of jam near Fairfield Museum on March 14 and 16, 1982.

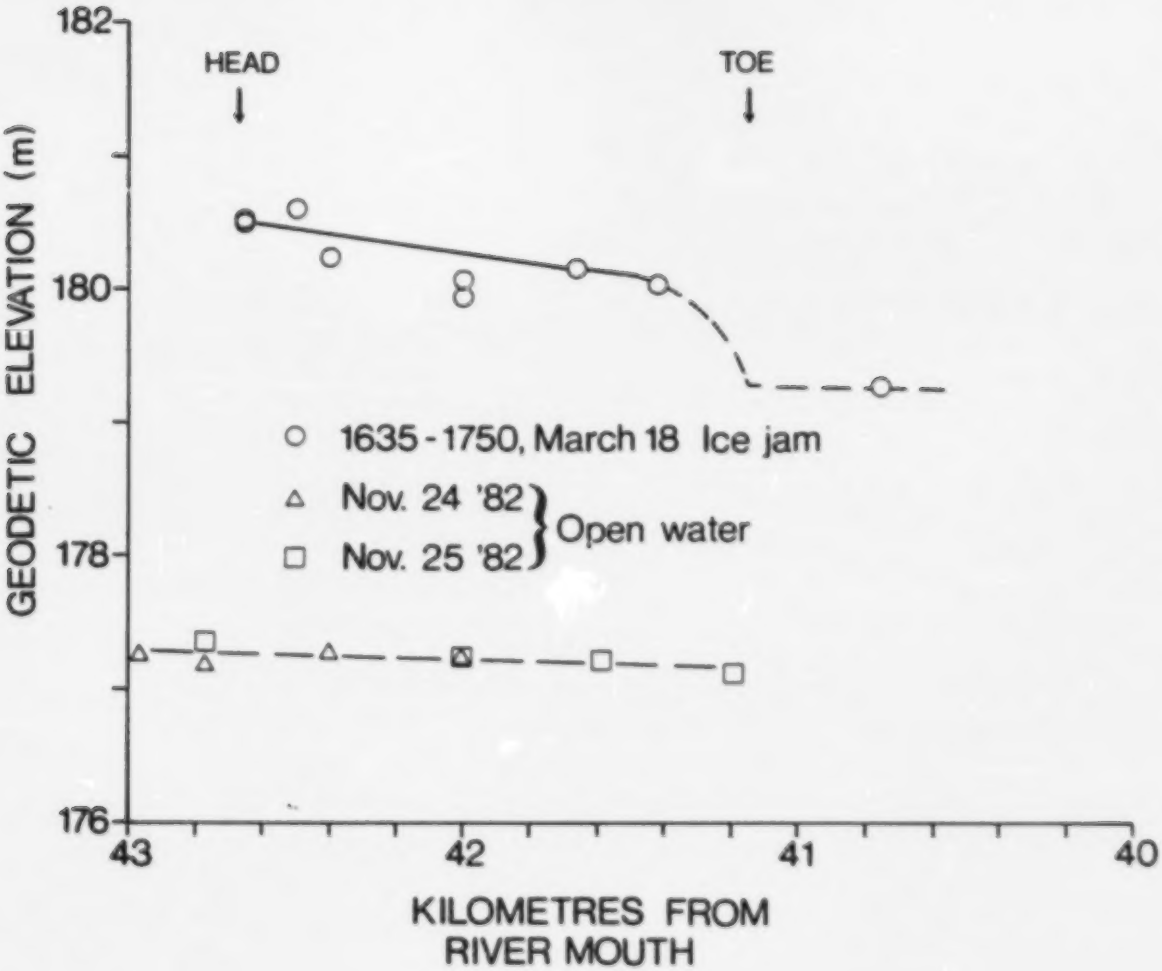


Fig. 16. Profile of jam near Louisville.

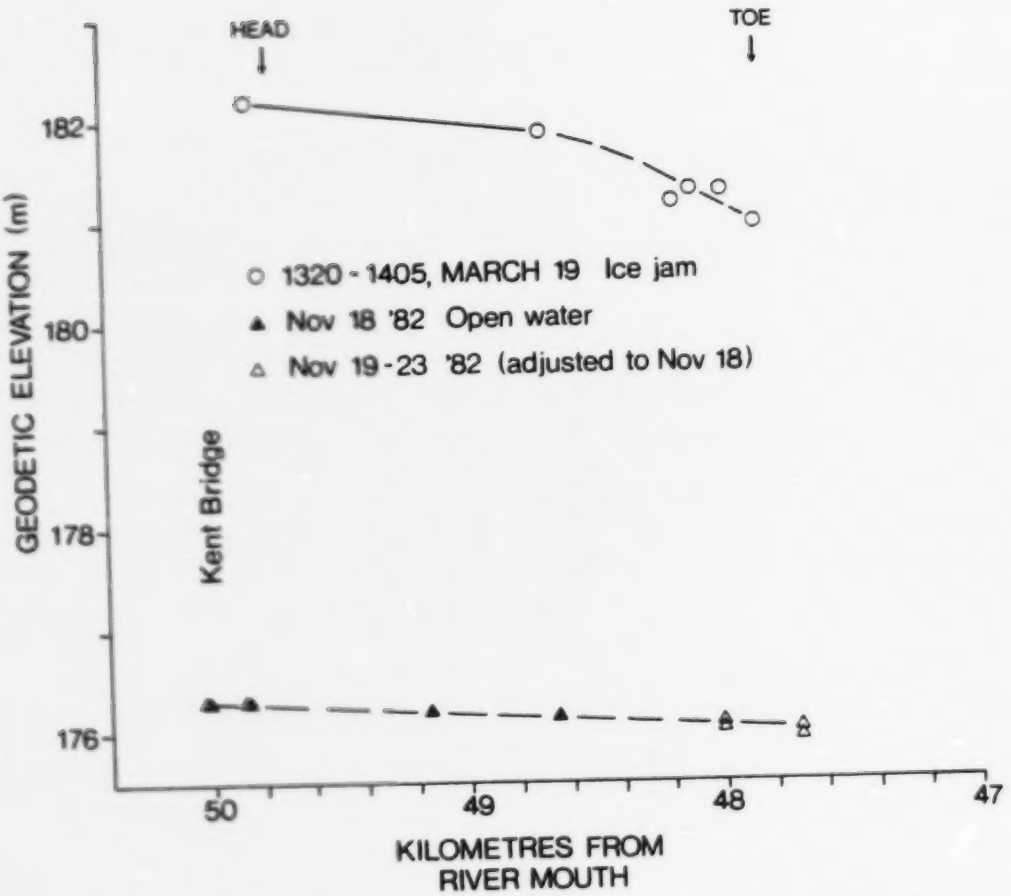


Fig. 17. Profile of jam downstream of Kent Bridge.

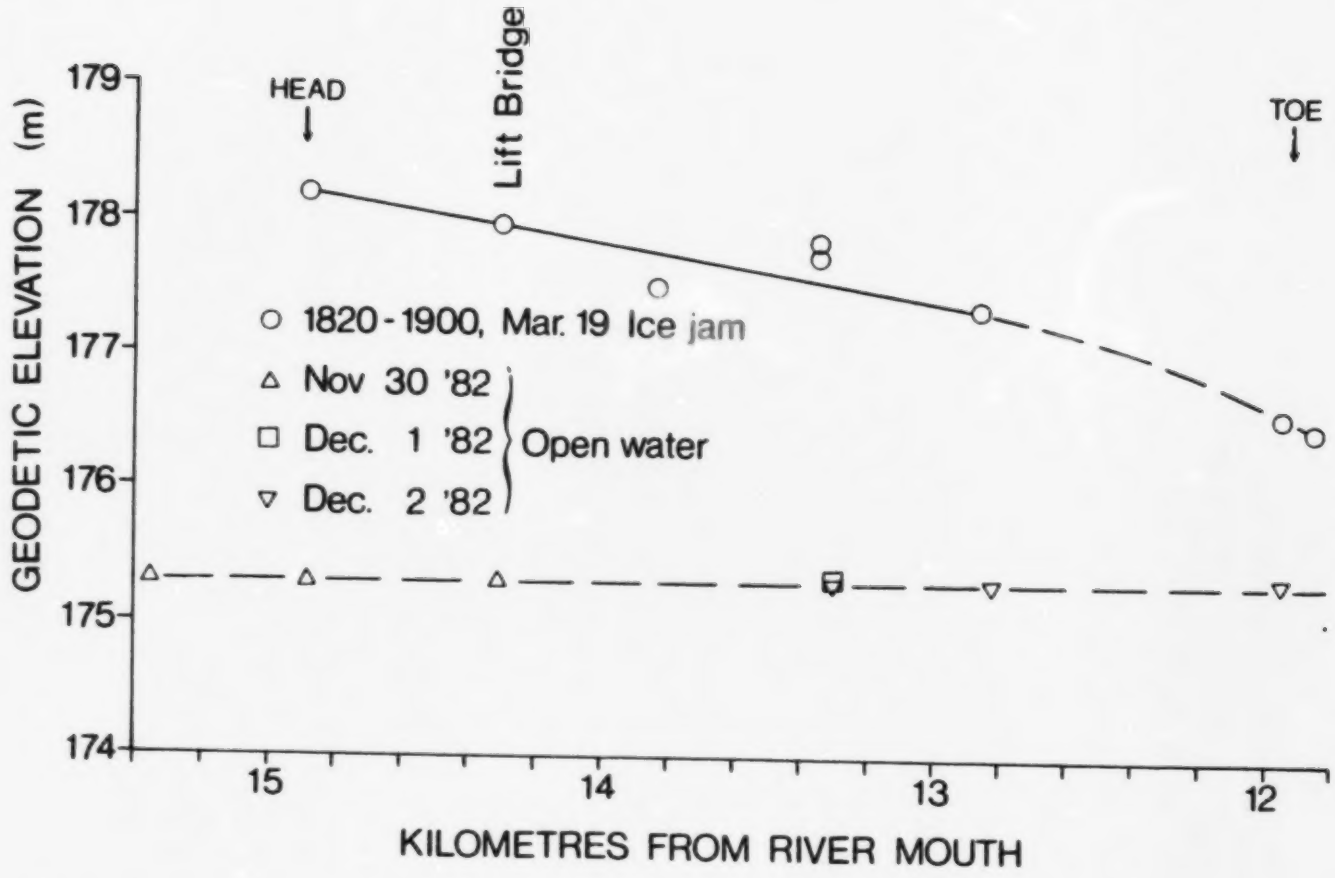


Fig. 10. Profile of jam near Prairie Siding

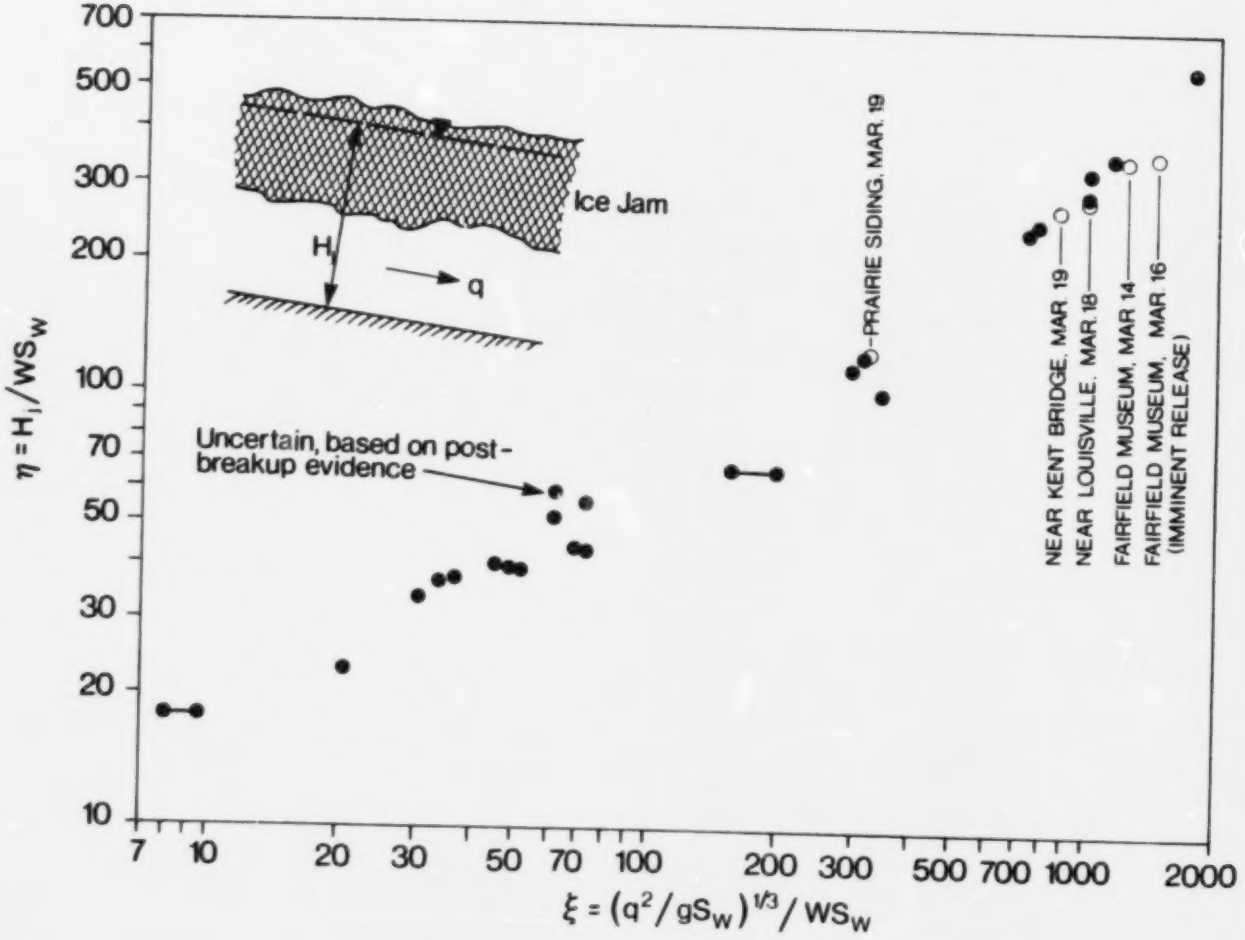


Fig. 19. Dimensionless depth versus dimensionless discharge for ice jams.

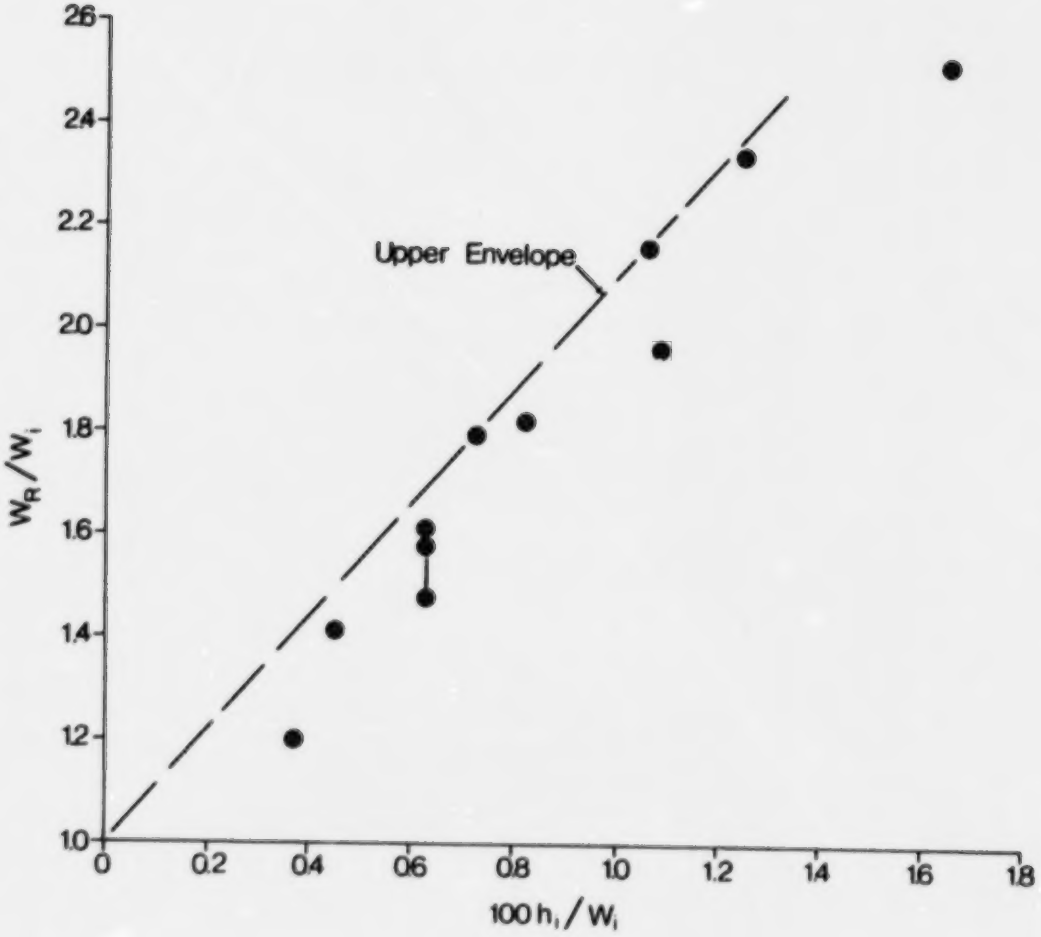


Fig. 20. Dimensionless plot of available data on ice jam releases above Chatham.

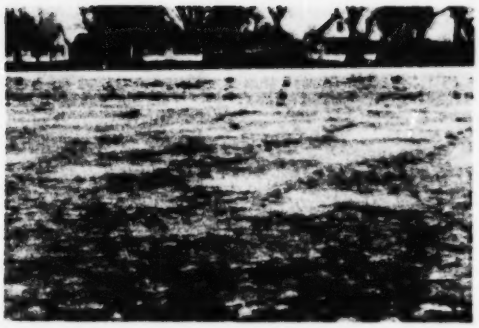
APPENDICES

Note:

For Appendices A and B, the following abbreviations have been used.

→	=	view toward
U/S	=	upstream
D/S	=	downstream
BDG	=	bridge
HWY	=	highway
RWY	=	railway
(*)	=	courtesy of LTVCA (Lower Thames Valley Conservation Authority)

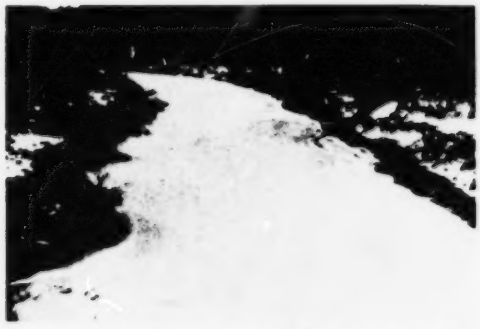
APPENDIX A: FREEZE UP AND WINTER



1. → RB, ICE COVER JUST U/S OF MOUTH, 1410 DEC. 12.

2. → U/S FROM HWY 21 BDG (THAMESVILLE), 1250 DEC. 26. NOTE OPEN AREAS

3. → U/S FROM MIDDLEMISS BDG, 1420, JAN. 6. NOTE OPEN AREAS



4. → U/S FROM DUTTON RD. BDG, 1250, JAN 5. INTACT ICE COVER

5. → U/S FROM KENT BDG, 1700 JAN 5. INTACT ICE COVER

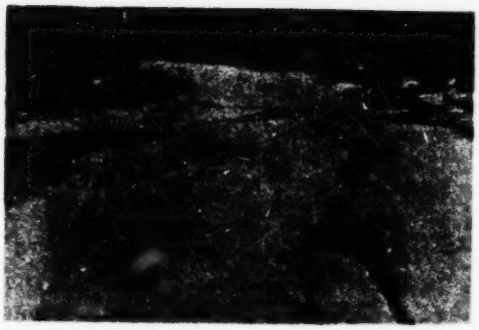
6. → U/S FROM SHERMAN BROWN BDG, 0740 JAN 6. INTACT ICE COVER

7. → U/S NEAR FAIRFIELD MUSEUM, 1230, FEB. 26. WINTER COVER.

8. → D/S FROM HWY 21 BDG, 1235, FEB. 26. WINTER COVER.

9. → D/S FROM KENT BDG, 1350, FEB. 26. WINTER COVER.

APPENDIX B: BREAKUP



10. → D/S FROM DUTTON RD. BDG, 1200, MAR. 15. NOTE LONGITUDINAL AND TRANSVERSE CRACKS.

11. → LB NEAR FAIRFIELD MUSEUM, 1450, MAR. 14. HEAD OF JAM.

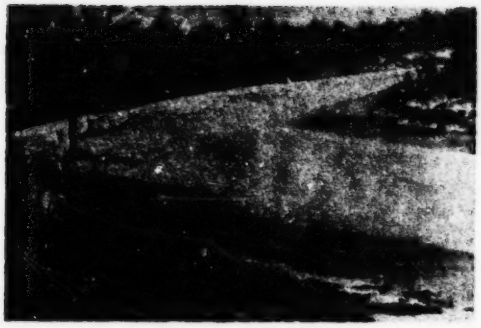
12. → U/S FROM HWY 21 BDG, 1015, MAR. 13. INTACT ICE COVER, OPEN SIDE STRIPS.

13. → RB D/S OF HWY 21 BDG, 1400 MAR. 13. INTACT ICE COVER, OPEN SIDE STRIPS (*).

14. → D/S FROM HWY 21 BDG, 1230, MAR. 14. SURFACE JAM.

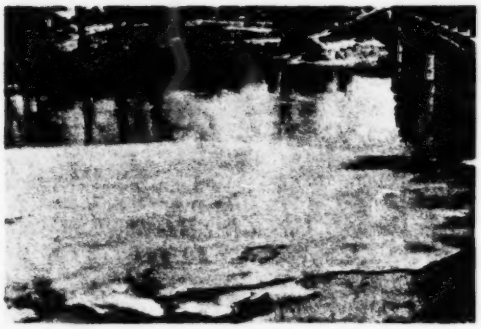
15. → D/S FROM HWY 21 BDG, 0820, MAR. 16. SURFACE JAM.

16. → U/S, 1310 MAR. 17. TOE OF JAM BELOW RWY BDG NEAR THAMESVILLE.



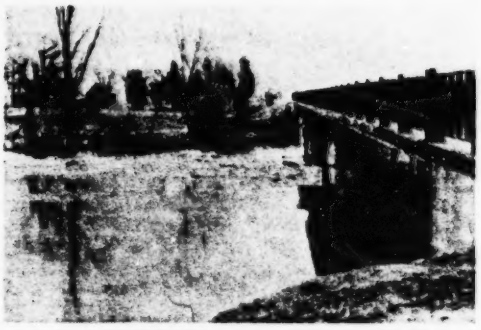
17. → U/S FROM KENT BDG, 1130 MAR. 13. INTACT ICE COVER AND OPEN SIDE STRIPS.

18. → LB AT KENT BDG, 1720 MAR. 14.



19. → LB AT KENT BDG, 0930 MAR' 17.

20. → U/S FROM KENT BDG, 0840, MAR. 19. NOTE ICE JAM AND COMPARE WITH PH. # 17.



21. → LB AT KENT BDG AFTER JAM RELEASE, 1025, MAR. 19.

22. → D/S FROM KENT BDG, 1000 MAR. 17 (•).

23. → U/S ~ 2 KM ABOVE GOLF COURSE, 1330 MAR. 13. INTACT ICE COVER AND OPEN SIDE STRIPS (•).

24. → D/S AT BEND OF PREVIOUS PHOTO ~ 1300 MAR. 17.

25. → RB, TOE OF JAM BELOW KENT BDG, 1343 MAR. 19.

26. → U/S NEAR TOE OF JAM BELOW KENT BDG, 1343 MAR. 19.

27. SAME VIEW AS IN PREVIOUS PHOTO, DURING RELEASE OF JAM. NOTE MOVING ICE AND HIGHER STAGE. 1350 MAR. 19.

28. → U/S NEAR GOLF COURSE, 0915 MAR. 14. NOTE BROKEN ICE OVER MAIN COVER, FROM TRIBUTARY CREEK ON LB.

29. → D/S, JAM NEAR LOUISVILLE, 1635 MAR. 18.

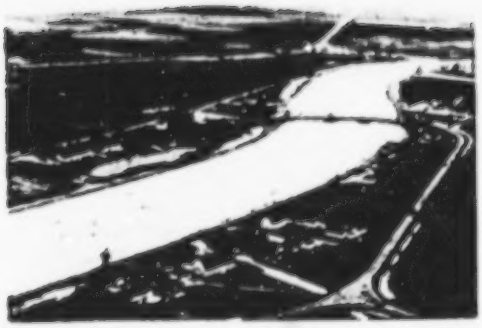
30. → LB. TRANSVERSE CRACK NEAR LTVCA OFFICE (CHATHAM) MAR. 16 (*).

31. → LB. TRANSVERSE CRACK NEAR HOLIDAY INN (CHATHAM), 0900 MAR. 15.

32. → D/S FROM THIRD ST. BDG IN CHATHAM. TOE OF SHORT JAM, 1000, MAR. 16.

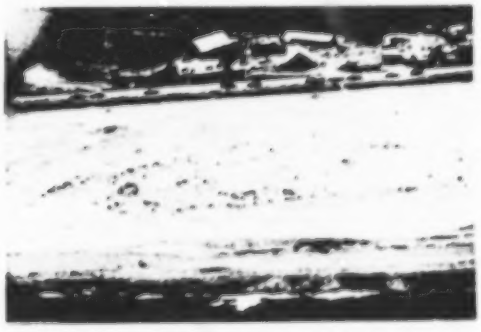
33. → U/S FROM THIRD ST. BDG. EXTENT OF SHORT JAM, 1000 MAR. 16.

34. → RB 1155 MAR. 18. TOE OF SHORT JAM NEAR HISTORICAL SITE BELOW CHATHAM.



35. → D/S ~ 1300 MAR' 19. JAM NEAR PRAIRIE SIDING (*).

36. → U/S, 1700 MAR. 19. HEAD OF JAM NEAR PRAIRIE SIDING (*).



37. → RB, 1700 MAR. 19, TOE OF JAM NEAR PRAIRIE SIDING (*).

38. → U/S AT TOE OF JAM NEAR PRAIRIE SIDING, 1807 MAR. 19.

39. → LB AT TOE OF JAM NEAR PRAIRIE SIDING, 1758 MAR. 19.

40. FLOODING ON RB U/S OF PRAIRIE SIDING, 1520 MAR. 19.

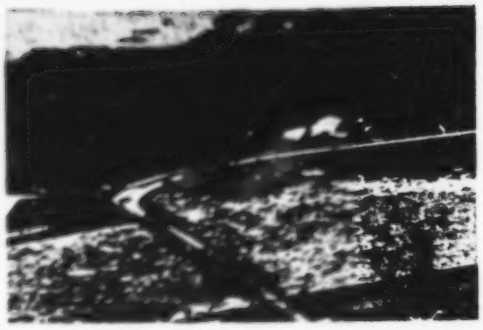
41. FLOODING ON RB U/S OF PRAIRIE SIDING, 1700 MAR. 19 (").

42. FLOODING ON RB U/S OF PRAIRIE SIDING, 1700 MAR. 19 (").

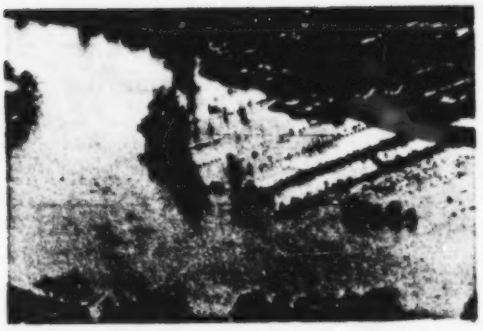
43. FLOODING ON BOTH SIDES, " LB, 1700 MAR. 19 (").

44. WATER OVER RIVER RD NEAR PRAIRIE SIDING, MAR. 19. (").

45. WATER NEAR RIVER RD ABOVE PRAIRIE SIDING, 1515 MAR. 19.



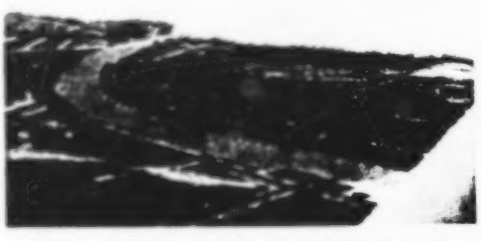
46. → RB, 1350 MAR. 20. ICE JAM NEAR PRAIRIE SIDING.



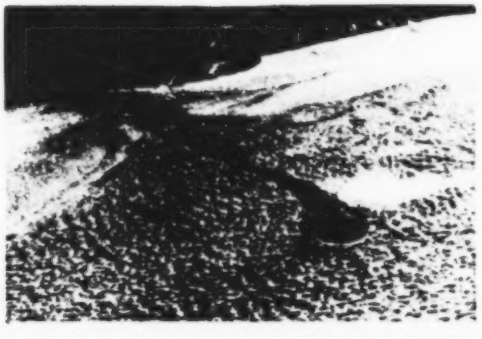
47. → D/S, 1400 MAR. 20. FLOODING BELOW PRAIRIE SIDING.

48. ICE BREAKING AT RIVER MOUTH, 1800 MAR. 13.

49. → U/S AT MOUTH, 1300 MAR. 17. OPEN SECTION DUE TO ICE BREAKING.



50. → D/S NEAR MOUTH, 0900 MAR. 20. OPEN SECTION DUE TO ICE BREAKING (*).



51. → U/S TO MOUTH. RIVER ALL CLEAR OF ICE. 1600 MAR. 22 (*).

APPENDIX C

WATER LEVELS AND ICE CONDITIONS: THAMES RIVER AT THAMESVILLE (HWY 21)

Date (March '82)	Time (24 hour clock)	Gauge Height (m)	Remarks
11	0900	11.39	
	1300	11.42	
	1630	11.45	
	2130	11.63	
12	0845	11.84	
	1245	11.95	
	1620	12.07	
	2045	12.22	Ice cover; open water at sides
	2300	12.26	Ice cover; open water at sides
13	0800	12.84	Ice cover; more open water at sides
	1012	13.17	No change
	1020	13.18	No change
	1207	13.48	No change
	1329	13.70	No change
	1504	14.00	No change; ice cover ≈70% of width
	1550	14.16	No change
	1620	14.29	No change;
	1643	14.36	No change
	1700	14.39	No change
	1746	14.54	No change
	1818	14.68	No change
	1908	14.84	No change
	2006	15.09	Ice cover ≈60%
	2045	15.27	"Breakup Initiation" between 1908 h and 2045. Ice has moved; new sheet of ice under the bridge.
	2147	15.52	Open water under bridge; extends ≈300 m upstream and 100 m downstream.
14	0735	16.48	Covered with large ice sheets; surface jam
	0854	16.52	Covered with large ice sheets; surface jam
	0851	16.45	Tape and wt = 7.14 m; surface jam; toe is ≈1.1 km downstream of bridge, head is .7 km upstream of bridge.
	1050	16.55	No change.
	1135	16.57	No change.
	1213	16.58	No change.
	1316	16.57	No change.
	1610	16.64	No change.
	1624	16.65	No change.
	1705	16.63	No change.
	1740	16.67	No change.
	2010	16.69	No change.
	2200	16.73	No change.

WATER LEVELS AND ICE CONDITIONS: THAMES RIVER AT THAMESVILLE (HWY 21) cont.

Date (March '82)	Time (24 hour clock)	Gauge Height (m)	Remarks
15	0806	16.68	No change, water level peaked @ 2400h.
	1036	16.67	No change.
	1327	16.67	No change.
	1555	16.65	No change.
	1745	16.78	No change.
	1810	16.79	No change.
	2010	16.80	No change.
16	0827	16.86	Ice jam has packed and moved downstream, head is only 70 m upstream of bridge.
	0915	16.87	No change.
	1030	16.89	No change.
	1215	16.91	No change.
	1434	16.93	No change.
	1625	16.96	No change.
	1740	17.02	No change.
	2000	16.91	Open water upstream and downstream; recorder chart shows a sharp peak of 17.12 m @ ≈1870h, then a sharp drop to 16.76 m @ 1850h. Presume ice moved out at 17.12 m. Surface speed ≈ 1 m/s.
17	0845	17.29	Open water.
	1040	17.32	Open water.
	1603	17.50	Open water.
18	0848	17.55	Open water.
	0950	17.56	Open water.
	1430	17.60	Open water.
20	0921	16.40	Open water. Water level falling.

APPENDIX D

WATER LEVELS AND ICE CONDITIONS: THAMES RIVER AT KENT BRIDGE

Date (March '82)	Time (24 hour clock)	Geodetic Elevation of Water Level (m)	Remarks
13	1125	176.87	Ice cover; open water at sides.
	1623	177.57	Ice cover; open water at sides.
14	0853	179.09	As above; evidence of some breakage.
	1205	179.31	There has been local movement and breakage downstream of bridge.
	1334	179.40	No change.
	1416	179.40	No change.
	1500	179.46	No change.
	1530	179.49	No change.
	1600	179.49	No change.
	1645	179.55	No change.
	1725	179.58	No change.
15	0819	179.79	No change.
	1100	179.79	No change.
	1330	179.79	No change.
	1610	179.79	No change.
16	0751	179.79	There has been a slight shift upstream of bridge
	0900	179.82	No change.
	1030	179.82	No change.
	1120	179.85	No change.
	1230	179.85	No change.
	1345	179.85	No change.
	1436	179.85	No change.
	1515	179.88	No change.
	1625	179.88	No change.
	1940	180.13	The ice at bridge has shifted. A large ice block has wedged itself between the pier and the right bank. "Breakup Initiation" occurred between 1625h and 1940h.

WATER LEVELS AND ICE CONDITIONS: THAMES RIVER AT KENT BRIDGE (continued)

Date (March '82)	Time (24 hour clock)	Geodetic Elevation of Water Level (m)	Remarks
17	0740	180.55	The ice floe at the toe has wedged itself further between the pier and the right bank.
	0835	180.55	Tape and weight reading = 7.63 m (open). No change.
	1025	180.59	No change.
	1115	180.59	No change.
	1230	180.62	No change.
	1340	180.71	No change.
	1500	180.74	No change. Aerial reconnaissance revealed that the jam is 2 km long. The toe is at Kent Bridge.
	1545	180.77	No change.
	1600	180.77	No change. Tape and weight reading = 7.48 m (open).
	1655	180.79	No change.
	1830	180.86	A piece of the ice floe at the toe has broken off. The ice floe, however, is still held between the pier and the right bank. The ice downstream has broken into smaller pieces and has compressed itself.
	1950	180.92	No change.
18	0713	181.20	No change. Tape and weight reading = 7.04 m (open).
	0815	181.20	No change.
	1000	181.20	No change.
	1232	181.16	Ice upstream of bridge has shifted.
	1248		Ice begins to move.
	1249	181.38	Ice continues to move.
	1256	181.35	Ice continues to move.
	1302	181.32	Ice continues to move.
	1303		Ice stops moving.
	1305	181.35	
	1323	181.26	
	1328	181.26	The front of the toe moved downstream and stopped just upstream of the bridge.
	1435	181.26	No change. Tape and weight reading = 7.01 m. Velocity ≈ 1.6 m/s.
	1506	181.32	No change.
	1525	181.32	No change.
	1530	181.38	No change.
	1706	181.41	No change.
	2005	181.47	No change.

WATER LEVELS AND ICE CONDITIONS: THAMES RIVER AT KENT BRIDGE (continued)

Date (March '82)	Time (24 hour clock)	Geodetic Elevation of Water Level (m)	Remarks
19	0725	181.38	No change.
	0848	181.35	No change.
	1025		Jam released.
	1030	181.71-181.87	(Ice levels). Velocity can be determined from the movies taken during the run.
	1035	181.71-181.87	(Ice levels).
	1038	181.71-181.87	(Ice levels).
	1053	181.87-182.02	(Ice levels). Most of the ice floes have passed Kent Bridge. The jam is arrested further downstream and the head of the jam is ≈.3 km downstream of Kent Bridge.
	1057	181.99	Open.
	1100	182.09	Open.
	1102	182.02	Open.
	1105	182.02	Open.
	1113	182.08	Open.
	1115	182.11	Open. Velocity ≈ 1.4 m/s
	1118	182.14	Open.
	1120	182.17	Open.
	1121	182.20	Open.
	1125	182.23	Open.
	1140	182.29	Open.
	1150	182.29	Open.
	1318	182.35	Open.
	1343		Toe of the jam just downstream of Kent Bridge is at Spot 6A*. Jam released at 1343.
	1403	181.80	Open. Velocity = 1.8 m/s
20	0932	180.43	Open.

* Spot 6A is sharp bend located 2 km below Kent Bridge.

APPENDIX E

WATER LEVELS AND ICE CONDITIONS: THAMES RIVER AT SHERMAN BROWN BRIDGE

Date (March '82)	Time (24 hour clock)	Elevation of Water Level (m)	Remarks
13	1600		Ice cover; small strips of open water at sides.
14	0935	177.45	No change.
	1150	177.54	No change.
15	1425	177.60	No change.
16	0740		No change.
	1135	177.54	No change.
	2100		No change.
17	0730	178.31	Ice deteriorated considerably; lateral cracks ≈50 m upstream of bridge; open water lead beneath bridge; lots of "brownish" spots on ice surface; open water enlarged by 1300h.
	0925		Ice still intact.
	1005	178.41	No change.
	1245	178.34	Original ice under bridge has moved.
	1330		No change.
	1630	178.41	Ice further deteriorated; no major changes.
18	0752	178.69	Ice upstream looks weaker but there was no movement; ice downstream of bridge shifted and compressed; larger open area.
	1052	178.71	No change.
	1600	178.71	No change.
19	0759	179.67	Ice level; jam from Louisville is under the bridge; head is ≈.2 km upstream of bridge,
	0820		Head is ≈.3 km downstream of bridge and moving. Surface speed ≈1.4 m/s.
	0828	179.44	Water level; open under bridge.
	0830		Head is out of sight.
	0900	179.24	Water level; surface speed ≈1.5 m/s.
	1019	179.29	Water level; surface speed ≈1.4 m/s.
20	0954	179.00	Water level; open.